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Central European University in part fulfilment of the

Degree of Master of Science

Sustainable Energy Transition in Mexico

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Luis Felipe Mora Solis

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Abstract

submitted by: Luis Felipe MORA SOLIS

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<This thesis presents a general sense of the techno-economic, socio-technical, and political perspectives of the Mexican energy system, with the purpose of solving the question of what kind of projects should be carried out in the country to reach carbon neutrality by 2050. The most relevant points found are that Mexico has a robust oil and natural gas infrastructure, fuels which have declined in production and are increasingly dependent on imports, mainly from the USA. In contrast, it is estimated that if solar photovoltaic and wind power capacity continue growing for one more decade at the same rate as the last 5 years, renewable energy sources will provide as much electricity as the total current generation system. In that sense, integration of renewable energy systems to the grid, energy efficiency and the production of hydrogen from renewable sources are presented as important innovation systems to keep using current infrastructure, avoiding lock-in's problems, and enhancing the future sustainable energy system. It is concluded that Mexico is in many ways a privileged country to initiate a sustainable energy transition, and the major element will be the disposition in terms of policy. >

Keywords: energy transition, sustainable energy, Mexican energy system, techno-economic perspective, socio-technical perspective, political perspective, energy policy.

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In advance, the author apologizes for any lack of attention to content, references or bias associated with this work.

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1. Introduction

More than a century ago, scientists hypothesized and predicted the consequences and implications of greenhouse gas (GHG) emissions to the atmosphere (Araujo,2018). Nowadays, the relationship between economic development and environmental impact has been widely studied. Some of the work conducted by environmental scientists and engineers has resulted in despair and frustration. For more than half a century, environmental scientists have fervently insisted on the catastrophic consequences of a lifestyle dependent on unsustainable, polluting, centralized, carbon intensive and unfair energy systems. However, global civilization has continued to increase unsustainable practices ever since, ignoring the warnings of researchers. Compared to previous decades, the current civilization and global economic system are more mature and dependent on energy systems that are not resilient to the impacts of climate change, which has been accelerated by the lack of adequate management of the residues of these energy systems. This trend can be considered accurate at both the global and national level.

Under the same context and emphasizing the country to be analysed in this thesis, the current Mexican energy system is investing in a new refinery, with a capacity of 400,000 daily barrels of oil, while continuously increasing the consumption of natural gas from the USA to produce electricity. Both actions are the exact opposite of what previous reports and researchers recommend. Again, like in past decades, the opinion and research of experts is being ignored. Unfortunately for global society and Mexican citizens, this time the consequences of climate change will be suffered not by future generations, but by the current one.

For these reasons, this thesis aims to examine the set of technoeconomic, sociotechnical, and political projects that Mexico must develop to reach carbon neutrality in their energy sector by 2050. The main purpose of this research is to present evidence on sustainable national energy transitions, its contexts, drivers, and barriers through a systematic literature review, to provide

evidence-based advice to Mexican policy makers on what steps need to be taken to achieve net-zero energy systems. This study is highly influenced by Kathleen M. Araujo's book "Low Carbon Energy Transitions", as well as the research paper published by Cherp et al "Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework".

Chapter 2 presents a literature review in chronological and topic-oriented order. This section presents previous research done by academics such as Araújo, Cherp, Grubler, Grubb, Geels, Jewell, Stern, Rogelj, Sgouridis, Markard, Foxon, among others. This section also intends to give a brief but clear definition of key concepts like sustainability, energy transition, as well as the main differences between renewable energy, low-carbon energy, clean energy, energy efficiency, energy security, and energy justice.

In chapter 3, the analytical framework and methodology of this work is presented, describing Cherp and colleagues' (2018) meta-theoretical framework for identifying the technoeconomic, sociotechnical and political perspectives for describing and analysing national energy transitions. This methodology assumes three different perspectives to identify, conceptualize and understand the relationship between the co evolution of three main systems: the energy markets and flows, the energy technologies, and the policies. As a result of this understanding, the information is used to develop policy recommendations within the Mexican context.

Chapter 4 analyses the three perspectives described in the methodology section within the specific context of Mexican energy systems. The techno economic section describes the resources, infrastructure, demand of petroleum, natural gas, and renewable sources of energy, mainly solar and wind in Mexico. In the sociotechnical section, the Mexican innovation niches, regimes, and systems are described, as well as the diffusion of some of the technologies that could help in their decarbonization strategies. For the political perspective, the state structure,

and goals in terms of energy system is discussed, as well as the current political interests that influence policy makers.

Chapter 5 presents the analysis and discussion of the key findings related to each of the perspectives, starting with a brief comparison between Mexico and the main fossil fuel producer countries. Also, an intersectional analysis is given, describing the key paths through which the Mexican energy system can achieve carbon neutrality by 2050. Finally, Chapter 6 presents the conclusion of this work, the research question is answered, and suggestions for projects that could be developed to achieve the goals are proposed.

2. Literature Review

This chapter aims to present previous research on the concept of energy transition, as well as its relationship with sustainable development, leading to the definition of sustainable energy transition. The chapter starts with a section on Global Climate Scenarios and Net Zero Energy Systems, where the most important points of the recent reports delivered by the United Nations Intergovernmental Panel on Climate Change (IPCC), and the International Energy Agency (IEA) report on Net-Zero roadmap, are discussed. To do this, a definition of the terms such as sustainable development, energy transition, renewable energies, low-carbon energy, clean energy, energy efficiency, energy security, and energy justice are stated.

Global Climate Scenarios and Net Zero Energy Systems

In 1972 the book "The Limits to Growth" was published by Jørgen Randers, William W. Behrens III, Donella H. Meadows and Dennis L. Meadows. Here, the authors designed a reliable mathematical model that showed the effect of human civilization on the finite environment. The model included feedback loops, so that in each interaction of the model, the change in values would depend on the most recent one, and not only on the initial condition. Their results showed that exponential growth increases over time, for example, if a parameter increases by 2% every year, it doubles in 35 years. Increases of 5% per year represent this doubling in 14 years, and so on. The final message was clear: small but constant changes every year represent doubling or tripling the values in the next decades.

After 50 years, the model designed for this investigation has proven to be one of the most successful econometric projections ever created. Analyses with more up-to-date data show results like those published in the first edition of the book, where the authors accurately exemplified the human capacity to quantify the ecological and environmental impacts of human activities, as well as demonstrated the human capacity to ignore inconvenient truths. The overall

forecast of the updated "Limits to Growth" is that there will be a significant difference in the economic development of societies in the middle of this century (Herrington, 2020).

Since then, researchers and policy makers have been addressing these issues. In the 1970s, the first unprecedented low-carbon energy transitions started to take place, mainly due to the global oil crisis. The motivations and main drivers of these transitions have been widely studied. One of the explanations points to the global oil crisis of 1972, which enabled and boosted action to stop dependence of this resource and to increase self-sufficiency and cost-competitiveness. Examples of these transitions are the ones implemented in France with nuclear energy, in Brazil with biofuels, in Denmark with eolic energy, and in Iceland with geothermal energy (Araujo, 2018).

However, these issues continue to pose a risk nowadays. Stern, N. (2015), argues that the most defining challenges of this century are managing climate change and overcoming global poverty, both which are interlinked. His research focuses on key issues that were highlighted by policymakers in the past decades, like discounting, modelling the risks of unmanaged climate change, climate policy targets and cost of mitigation. He examines the strategies with profound long-term effects on the structure and growth of an economy, and the uncertainties that will be faced in the coming decades. Regarding the costs of that mitigation, Stern estimates that the stabilization of the atmospheric concentrations of GHG are between 500 and 550 ppm of CO₂ equivalent, which would cost around 1% of the global Gross Domestic Product (GDP) per year. Moreover, he demonstrates that meeting the more demanding target of 1.5°C change in the average global temperature, would require an annual investment of no more that 2% of the global GDP.

Similarly, Stern emphasized the potential of integrated and mutually reinforcing approaches to climate, growth, and development, as well as the influence of new international cooperations

to conduct international climate coalitions focused on providing support for joint development and climate actions. Finally, he highlights the potential for growth and acknowledges that if countries were to understand the attractiveness of moving quickly to the decarbonization of their domestic economies, climate cooperation and mitigation would become more about coordination, sharing lessons and mutual support. He concludes by stating that, “the transition to low-carbon economy can be full of innovation, creativity and rising living standards to all relevant dimensions”.

On a similar note, Ribeiro, S. K., Roy, J., Urge-Vorsatz, D., & Figueroa, M. (2013), explore if it is possible to sustain economic growth with the increasing constraints of local and global environmental services, and within planetary boundaries. The authors discuss the importance of providing an interdisciplinary overview of energy end-use services in the context of sustainable development. Similarly, they demonstrate that one of the most prevalent challenges of the energy sector for sustainable development is to meet the increase in demand while at the same time reducing carbon intensity.

Furthermore, the latest Intergovernmental Panel on Climate Change (IPCC) report 2022 on climate change mitigation claims that “unless there are immediate and deep emissions reductions across all sectors, global average temperature of 1.5°C about preindustrial levels by 2100 is beyond reach”. Some of the sectors that the IPCC identifies as vital are energy, land use, industry, urban, buildings and transport. The international organism points out that these sectors must peak their GHG emissions no later than 2025, in other words, investment in high carbon energy technologies and practices must stop with immediate effect.

To illustrate, Figure 1 shows the mitigation options according to the key sectors presented by IPCC, including their contribution to net emission reduction and their respective range of cost of implementation. As seen in the graph, the most effective and cost competitive technologies

to generate electricity and reduce carbon emissions are from the energy, wind, and solar sectors. Combined, these technologies could account for annual savings ranging from 4 to 8 Gtons of CO₂ eq. Thus, there is a massive but expensive opportunity to reduce emissions from the Agriculture, Forestry, and other Land Use (AFOLU) sector, namely regenerative agriculture, and rewilding, which could sequester several Gtons of CO₂ eq every year. In the building sector, there is a potentially affordable opportunity of saving at least 2 Gtons of CO₂ every year, just by avoiding unnecessary demand and retrofitting lightning and insulation. It is noticeable that every sector has at least seven possible actions, and that several of the actions are economically competitive with current options.

In the same regard, the OCDE's energy agency, the International Energy Agency (IEA), released the "Report Net-Zero by 2050" in May 2021. The report presents a new regulatory and macroeconomic scenario that illustrates the actions needed to move the global economy towards carbon neutral operations by 2050. It highlights the need to invest USD\$ 5 trillion by 2030 in clean technologies to ensure the sustainable development goal of universal, clean, and affordable energy access and global air quality by 2030. Furthermore, it states that there is no need for further investment in fossil fuels, especially coal plants that have not been curtailed, and that by 2050 oil demand will be reduced to 24 Mbpd, dominated mainly by Russia and the Middle East.

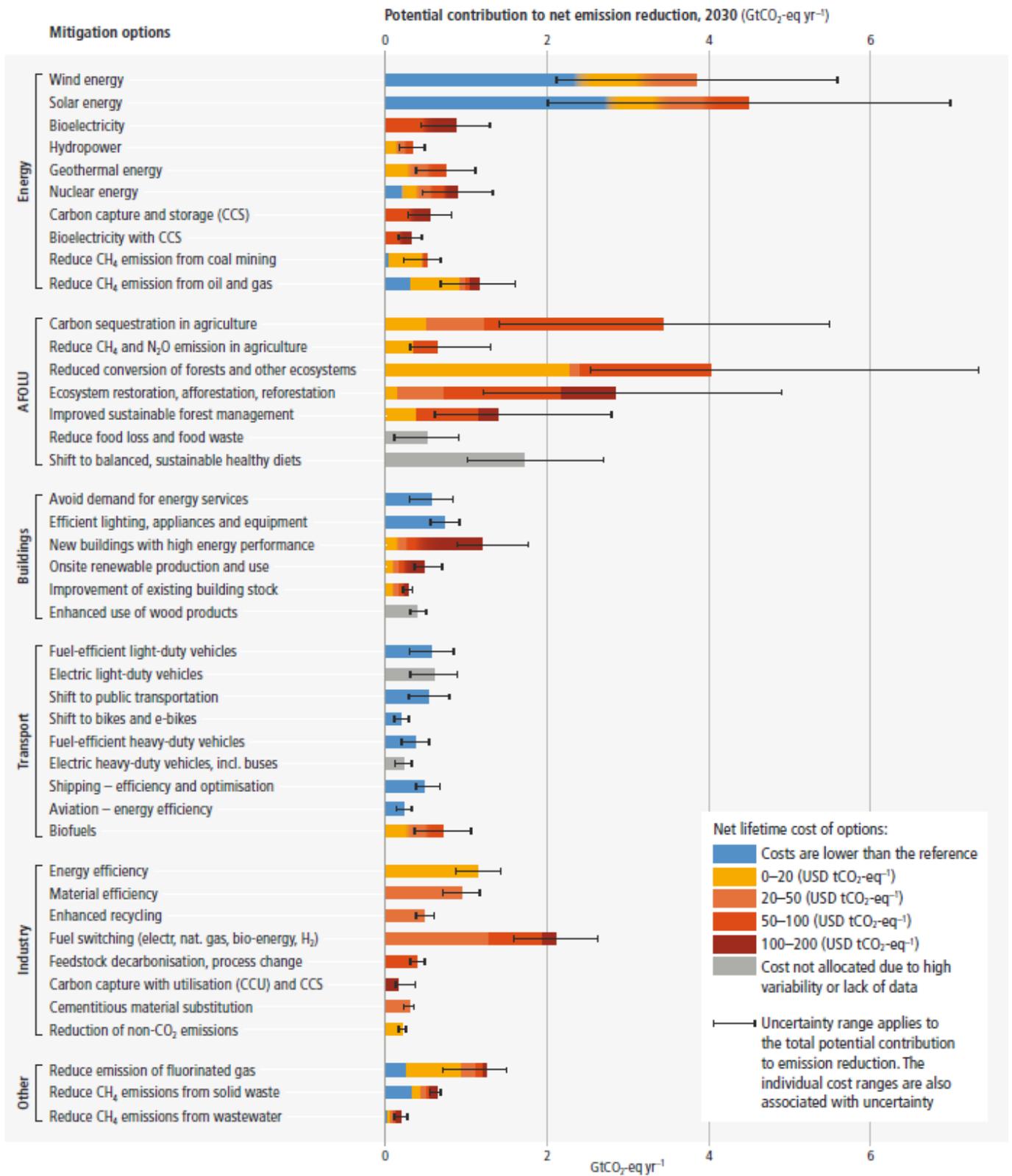


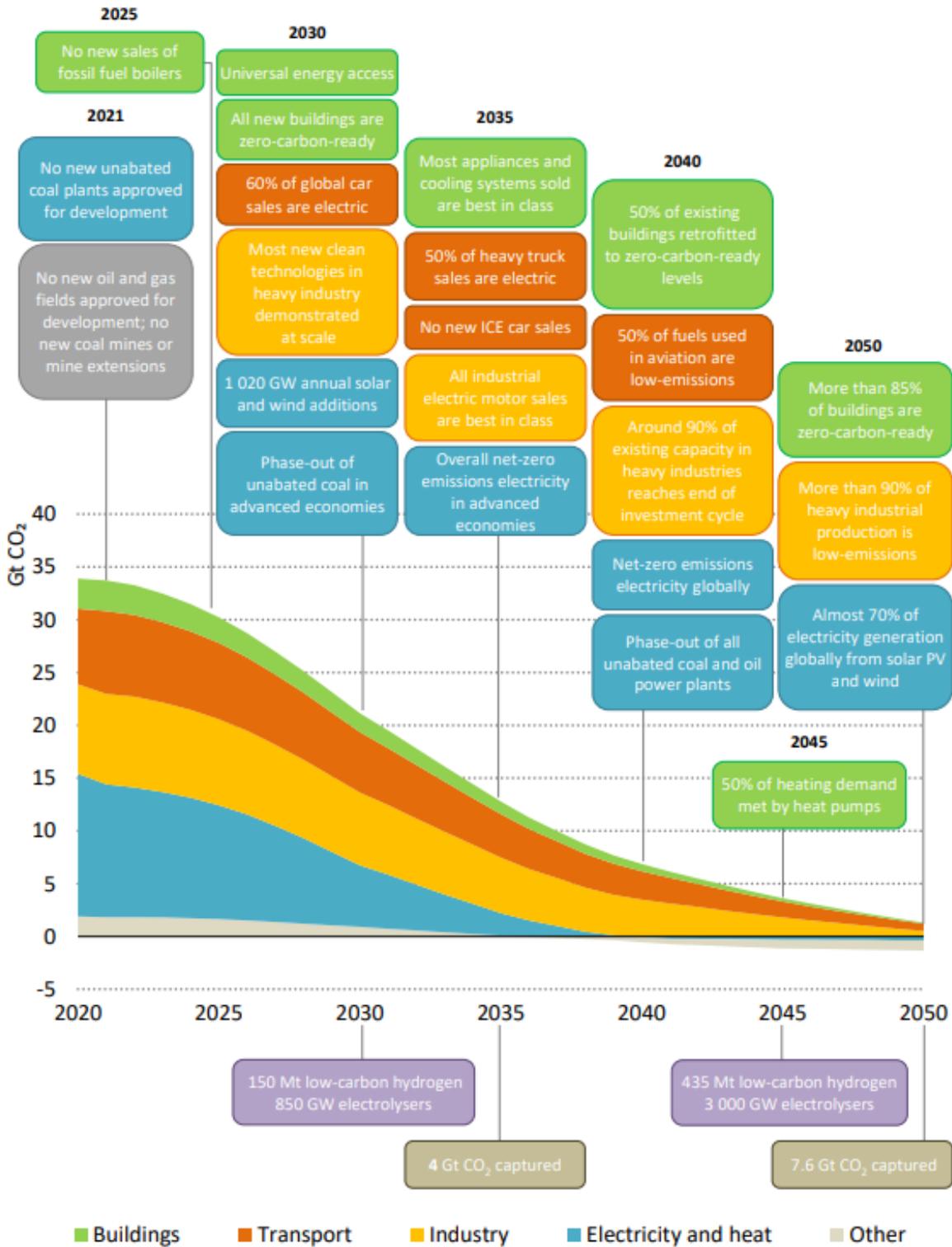
Figure 1 Mitigation Options and their Estimated ranges of costs and potentials in 2030. Source: IPCC 2022 Mitigation Report.

Compared to some of the IPCC scenarios, this one is considered low in Carbon Capture and Storage (CCS) and Bio Energy with Carbon Capture and Storage (BECCS) use (7.6 GtCO₂ by 2050), zero use of offsets in the power sector, medium in total final energy consumption (340 EJ by 2050), as well as high in final fuel demand from hydrogen (530 Mt by 2050), high in solar and wind energy use, electrification, and energy efficiency. In addition, this scenario envisages the disappearance of internal combustion car sales by 2035 and a carbon-free global electricity grid by 2040. According to this scenario, by 2030 there will be 1,000 GW of renewable energy capacity and global energy intensity will be 3 MJ/USDPPP\$, although this will require an historical increase in clean energy investments. The areas targeted for this large investment will be energy infrastructure, power grids, low-carbon fuels, energy storage and hydrogen infrastructure.

The report also highlights that the decades of 2020 and 2030 will be marked by "both accelerated deployment of the technology we already have and accelerated innovation to prepare for the next generation," where the key pillars will be clean electrification, energy efficiency and innovation, represented in the more than 400 milestones for the different sectors. To demonstrate, Figure 2 shows some of the IEA's key milestones to achieve reduced carbon emissions. The first reduction in GHG emissions to reach decarbonization comes from the no more investments in coal mines or mine extensions. The next one is the electricity sector, which will be the first and most important of the energy transition, because once the electricity sector decarbonizes its practices, many other sectors will try to use those technologies to power their operations. Still, the industry, transport and building sectors will decrease their emissions and reach carbon neutrality by half of the century.

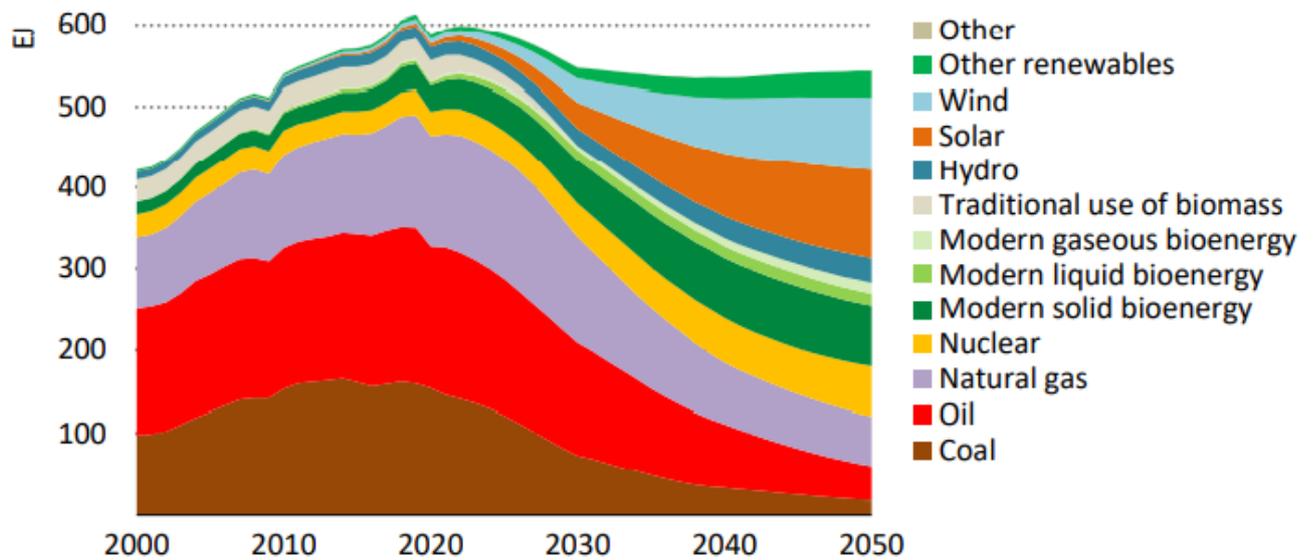
On a similar note, Figure 3 is important to analyse because it shows the specific technologies that will replace current use of fossil fuels, as well as the predictions of future energy consumption worldwide. As a result, there is going to be a considerable reduction in coal, oil

and natural gas use. The substituting energy sources will be solid and liquid bioenergy, wind and solar. Technologies like hydro, traditional biomass, and nuclear will remain constant.



CEU eTD Collection

Figure 2 Key milestones in the pathway to global Net-Zero emissions. Source: IEA, 2021.



IEA. All rights reserved.

Renewables and nuclear power displace most fossil fuel use in the NZE, and the share of fossil fuels falls from 80% in 2020 to just over 20% in 2050

Figure 3 Global Energy Supply by 2050. Source: IEA,2050.

To complement these findings, Davis, and colleagues (2018) propose a range of existing technologies that could meet future demands for the most difficult to-decarbonize services and processes without net addition to the CO₂ of the atmosphere. In their investigation, the authors discuss the prominent technological opportunities and barriers for eliminating and/or managing emissions related certain sub sectors, such as aviation, long-distance transport, shipping, production of carbon-intensive structural materials such as steel and cement, and provision of a reliable electricity supply that meets varying demand. Finally, they estimate that from the 34 Gtons of CO₂emitted from fossil fuels and industry sectors in 2014, 9.2 Gtons come from the difficult to decarbonize ones.

Figure 4 presents the schematic diagram of an integrated system that can provide essential energy services with zero emissions involved. It indicates the dominant role of specific technologies and processes, like clean power generation and transmission, clean fuel production and transportation, end use of materials, and carbon management. Moreover, the principal

power generation systems are solar, wind, hydro with pump storage, nuclear and thermoelectric plants with CCUS. The main fuels are hydrogen, synthetic hydrocarbons, and ammonia. Carbon management considers sources of carbon from thermoelectric plants, direct air capture, as well as cement and steel industries. Sinks of carbon are the synthetic fuels production and geologic storage.

The assertions regarding feasibility are not the result of formal, quantitative economic modelling. Instead, they are based on a comparison between the current and projected costs, with the stated assumptions about progress and policy. This model could be used in future research and applied to real regional case studies today, where their energy and material requirements could be quantified, as well as their emissions and the way in which these can interact in the integrated system.

It is vital to integrate currently discrete energy sectors and industrial processes. This integration may entail infrastructural and institutional transformations, as well as active management of carbon in the energy system. The rapid and effective change may depend on coordinating operations across energy and industry sectors, which could help boost utilization rates of capital-intensive assets. In practice, this would entail systematizing and explicitly valuing many of the interconnections described on their schematic diagram.

Authors proposed research in technologies and approaches that can decarbonize provision of the most difficult-to-decarbonize energy services, as well as systems integration research that would allow reliable and cost-effective provision of these services. They conclude that a successful transition to a future net-zero emissions energy system is likely to depend on the availability of vast amounts of inexpensive, emissions-free electricity, mechanisms to quickly and cheaply balance large and uncertain time-varying differences between demand and electricity generation, electrified substitutes for most fuel-using devices, alternative materials

and manufacturing processes including CCS for structural materials, and carbon-neutral fuels for the parts of the economy that are not easily electrified.

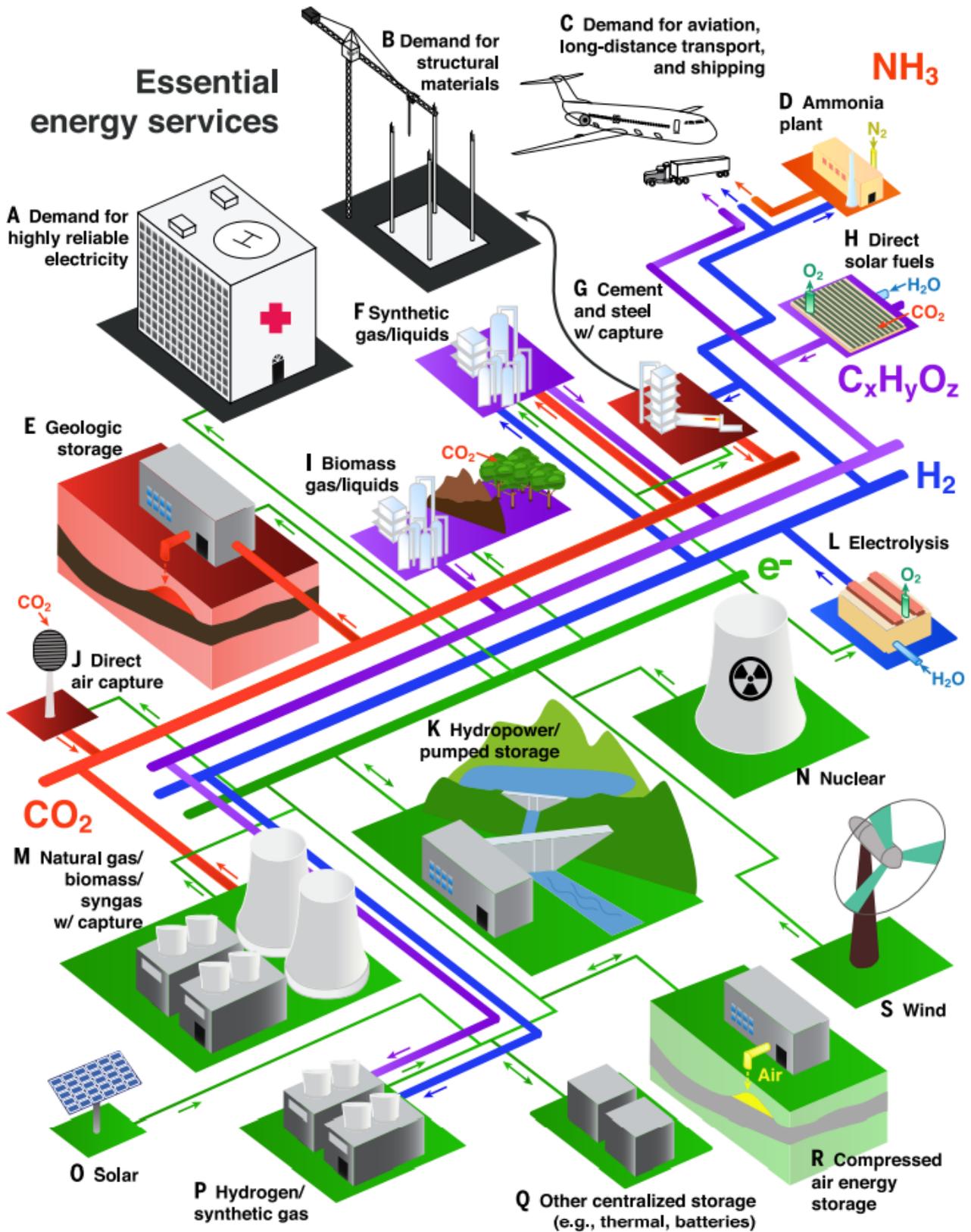


Figure 4 Schematic Diagram of an integrated system that can provide essential energy services. Source: Davis et al, 2018

Markard et al (2011) define a sustainability transition as a long-term and multidimensional set of processes that lead to fundamental shifts, involving technological, organizational, political, economic, social, and cultural aspects, which would let systems shift to modes of production and consumption rates suitable for the regeneration capacity of the surroundings. He concludes that the field of sustainability transition is complex and to fully comprehend its nature, it is necessary to involve disciplines such as economic geography, philosophy of science, management, sociology, policy studies and modeling.

Foxon (2011) proposed a multi-level micro-meso-macro coevolutionary framework to analyze transitions to low-carbon economies. He identifies as the key coevolving systems the **ecosystems**, defined as the natural flows and interactions that maintain and enhance living systems; **technologies**, as the methods and designs for transforming matter, energy and information from one state to another in pursuit of a goal; **institutions**, as ways of structuring human interactions; **business strategies**, as the means and processes by which firms organize their activities so as to fulfil their socio-economic purposes; and **user practices**, as the culturally embedded patterns of behavior relating to fulfilling human needs.

Grubler (2012) highlighted the importance of energy end-use and services, lengthy process of transitions and patterns that characterize a successful scale up. He argues that in energy transition matters, the demand has played an important role in shaping the supply, guarantying the need for the good and enhancing the market strengthening. Examples of this are the steam turbines enhancing the expansion in demand for coal, the petrochemicals driving the growth for oil industry, and the electronic devices giving rise to the electric utility companies. He

emphasised that energy innovation systems and policies driving energy transitions include continuity, alignment between policies and balance between supply and demand.

Grubb et al (2014) declare that energy system's development is a mixture of domains, catalogued as "satisficing", "optimising" and "transforming", depending on the economic school of thought, scale of time and characteristic on how energy systems behave. He points out that at least since the industrial revolution, nature of energy systems has been dependent on policy making.

Cherp et al (2014) define energy security as the low vulnerability of vital energy systems. They consider that the concept should answer the questions of security for whom, security for which values, and security from what threats. Also, they propose a way of measuring it in base of the availability, accessibility, affordability, and acceptability. Similarly, Brown et al (2014) present an energy security index and conclude that providing empirical evidence of availability, affordability, energy efficiency and environmental stewardship is how the key strategic components of energy security are ensured. They prove how OCDE countries have failed in terms on energy security between 1970 and 2010. They define energy security as the interconnection of the availability, affordability, efficiency, and stewardship dimensions. The conclusion is that most of industrialized countries had regresses in their energy security index and that successful countries focused on several but specific policy mechanisms to enhance energy efficiency.

Sgouridis and Csala (2014) define a Sustainable Energy Transition (SET) as a controlled process that leads to an advanced, technical society to replace fossil fuels primary energy inputs with sustainably renewable energy sources, maintaining sufficient energy service level per capita. To accomplish this, a coordinated transformation of both energy supply and demand is required. It involves the transformation of an economy based on energy stocks to an economy

based on renewable energy flows. They present 5 propositions that cover economic, social, and environmental aspects:

1. The rate of pollution is less than the ecosystem assimilate capacity.
2. The renewable energy generation does not exceed the long-run ecosystem carrying capacity nor irreparably compromises it.
3. Per capita available energy remains above the minimum level required to satisfy societal needs at any point during SET and without disruptive discontinuity in its rate of change.
4. Investment rate for the installation of renewable generation and consumption capital stock is sufficient to create a sustainable long-term renewable energy supply basis before the nonrenewable safely recoverable resource is exhausted.
5. Future consumption commitment is coupled to and limited by future energy availability.

Geels (2016), defines a low-carbon transitions as the long-term multi-faceted processes, and recommend that bridging the approaches may generate a more useful and insightful chain of assessments to support accurate policy formation and action. He mentions that Integrated Assessment Models (IAM's), socio-technical transition theory and practice-based action research are helpful approaches for analyzing low-carbon energy transitions. About IAM's, he emphasizes their capacity to foster future-oriented explorations of diffusion and costs of low carbon technologies and to assess sustainability outcomes, which eventually enhances strong body of knowledge to propose the accurate policies according to the specific target.

Araujo (2018) mentions that national energy transitions of any significance require several decades to appreciate accordingly. She emphasizes that currently, more than 80% of the world's primary energy consumption derives from mineral coal, petroleum, and fossil natural gas, from

decisions which were taken several decades before. Nevertheless, international organizations like United Nations, the World Bank and the World Economic Forum call for decarbonizing energy systems. So, the central question is how a national energy transition can be explained in terms of the inflection points and interventions by the government, industry, and civil society. Her book challenges how the evolving national energy strategies are interpreted.

The concept of sustainable energy transition may have different definitions depending on the context; therefore, a definition considered in this thesis, mainly influenced by Cherp and Araujo's previous work, is a long-term structural change in the energy system of at least 15% of the traditional energy sources with a low carbon alternative in each mix. It means the process of change over time of the infrastructure, institutions, and body of knowledge between the current energy systems and the ones desired by the middle and the end of this century. The interaction between society, natural systems, and technology, considering and analyzing every aspect and their interactions is imperative in giving a proper planning and management policy.

The term sustainability refers to durability of a system (Araujo, 2018), in other words, meeting the needs of current generations without compromising the ability of future generations to meet their own needs. The term renewable refers to the energy forms that naturally regenerates at a higher rate than the rate of consumption. Usually, this term includes forms of energy like solar, wind, bioenergy, geothermal, wave, tidal, etc. The term clean is used in the context of the fuel that does not pollute. The term low carbon refers to less carbon emission in reference to another source of energy, which implies the need for a clear scope.

Huhta (2021) points the contribution of energy law as pivotal in ruling energy dynamics for the pursuit of the low-carbon transition and aims to initiate a closer relationship between energy law and the other disciplines. As Cara Daggett mentions in her book "The birth of Energy", Energy is perhaps the main problem to solve the Anthropocene" and that the problems of

Anthropocene will demand radical political change. She argues that energy tends to be reified, privatized, and individualized when it becomes an object of politics.

3. Analytical Framework and Method

3.1 Analytical Framework

In this section, the meta-theoretical framework for national energy transitions is described. The framework proposed by Cherp et al (2018), assumes three different perspectives to conceptualize the co evolution of three main systems: the energy markets and flows, the energy technologies, and the policies. This enables the establishment of the Techno-Economic, the Socio-Technical and the Political perspectives. The authors mention that the most prominent factors shaping the energy transitions are the economic development, technological innovation, and policy change. They focused on the energy sector at a national size and defined an energy transition as the change in the state of an energy system as opposed to a change in individual energy technology or fuel source. Also, an Elinor Ostrom's approach was followed, which considers the relationship between these perspectives to explain national energy transitions

through theories from each perspective. They emphasised the elevated role of political science since policies are highly relevant in shaping energy transitions by this century.

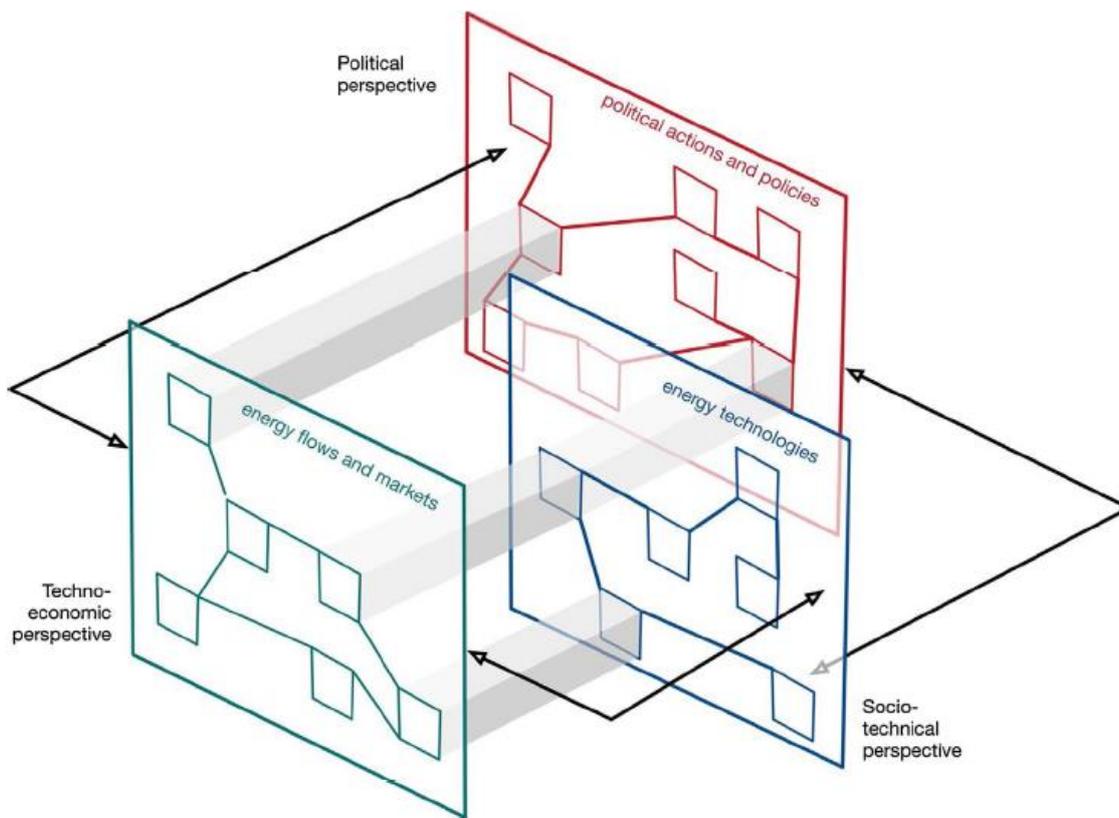


Figure 5 Co-relation between the perspectives on national energy transitions. Source: Cherp et al (2018)

The techno-economic perspective describes the natural resources from which the energy systems are fuelled and powered, the demand of the service or product, and the infrastructure of the energy systems on a country analysed. It focuses on the current energy flows, such as fuel availability, reserves, costs, and prices of import-export, cost of technologies, type, and potential of renewable energies.

The socio-technical perspective includes the understanding on innovation systems, regimes, niches, and technology diffusion. It focuses on the existence and development of innovation systems, the coordination between regimes and niches, along with their interactions, as well as

the understanding of global maturity of energy technologies and the diffusion of these knowledge.

The political perspective focuses on the changes in policies that affects directly or indirectly the energy systems in terms of a national State. The institutions are defined as the structures that enable and constrain state and political actors. The capacities mean the potential of a state to accomplish any energy policy it desires. Other important elements of this perspective are the government system, political interests, state goals and the international influence. The representation of the framework and the perspectives, along with their interactions is presented in Figure 5.

3.2 Method

This study intends to present the perspectives proposed above, for the practical case of Mexico, with the purpose of identifying the most relevant points of each perspective and thus provide proposals for emission reduction policies in the Mexican energy sector. Therefore, the sources of information used for this research are described below.

Data and graphics on population, gross domestic product (GDP), primary energy consumption (PEC), and carbon dioxide emissions are obtained from the Our World in Data database, which were obtained from BP Statistical Review of World Energy, Ember's Global Electricity Review and Global Carbon Project.

Some documents used to show data and images about infrastructure maps of the Mexican energy system are:

- Mexico Energy Outlook, Special Report, by International Energy Agency, 2016.
- Energy Policies Beyond IEA Countries, by International Energy Agency, 2017
- Mexico Energy Profile, International Renewable Energy Agency, 2019

- Mexico Clean Energy Report, by U.S. Department of Energy and National Renewable Energy Laboratory (NREL), 2021.
- Country Analysis Executive Summary: Mexico, by U.S. Energy Information Administration, 2020.

In Chapter 4, the Technoeconomic, socio-technical and political perspectives will be presented, from a general approach to the Mexican national level.

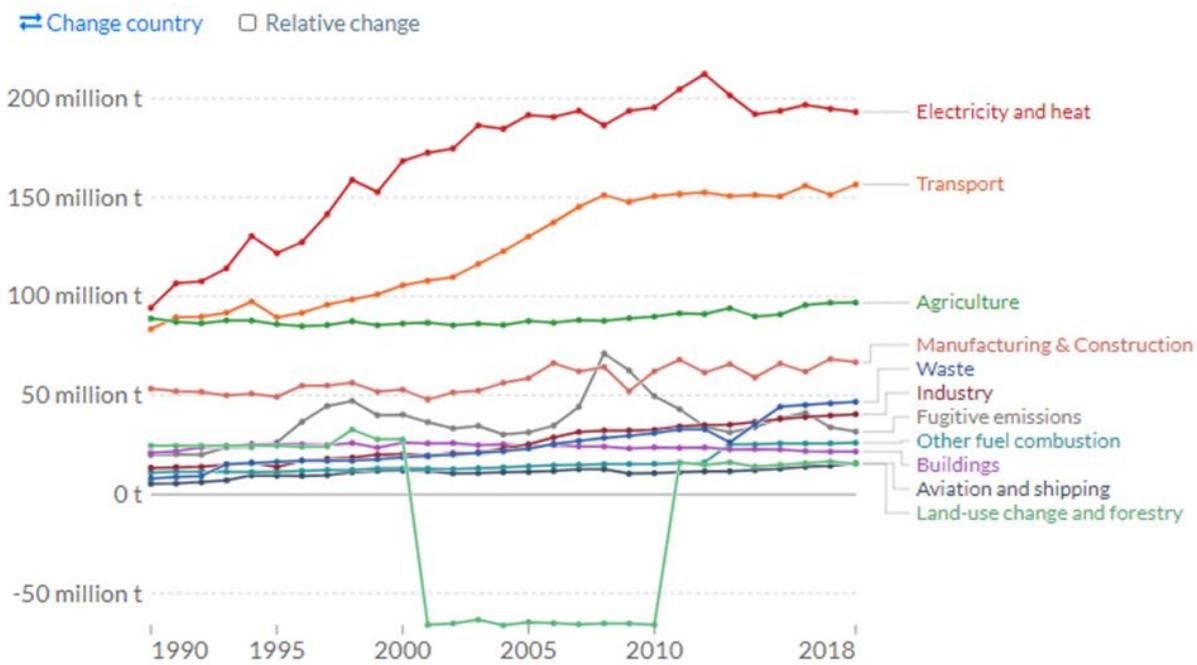
4. Results: Sustainable Energy Transition in Mexico, a novel idea.

This chapter has the purpose of applying the theory on sustainability and national energy transitions in Mexico. First, a brief description of the greenhouse gases emissions in Mexico is presented, as well as a comparison of the primary energy consumption between some of the most representative countries around the world and the Latin American region. Finally, the results of the most representative techno-economic, socio-technical, and political perspectives of this country will be discussed.

Mexico is a country with a population of more than 128 million people (2022), land surface of 1.96 million km², Gross Domestic Product (GDP) of roughly USD\$ 1.2 trillion, Primary Energy Consumption (PEC) of 2,100 TWh/year and Annual CO₂ emissions of 435 Mtons/year. Located at the centre of the American continent, it shares borders at its north with the USA, at the south with Guatemala and Belize, as well as the Atlantic Ocean at the West and the Pacific Ocean to the East. Politically speaking, it consists of a republic with 32 States and a total of 2,471 municipalities.

Greenhouse gas emissions by sector, Mexico

Greenhouse gas emissions are measured in tonnes of carbon dioxide-equivalents (CO₂e).



Source: CAIT Climate Data Explorer via Climate Watch OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY

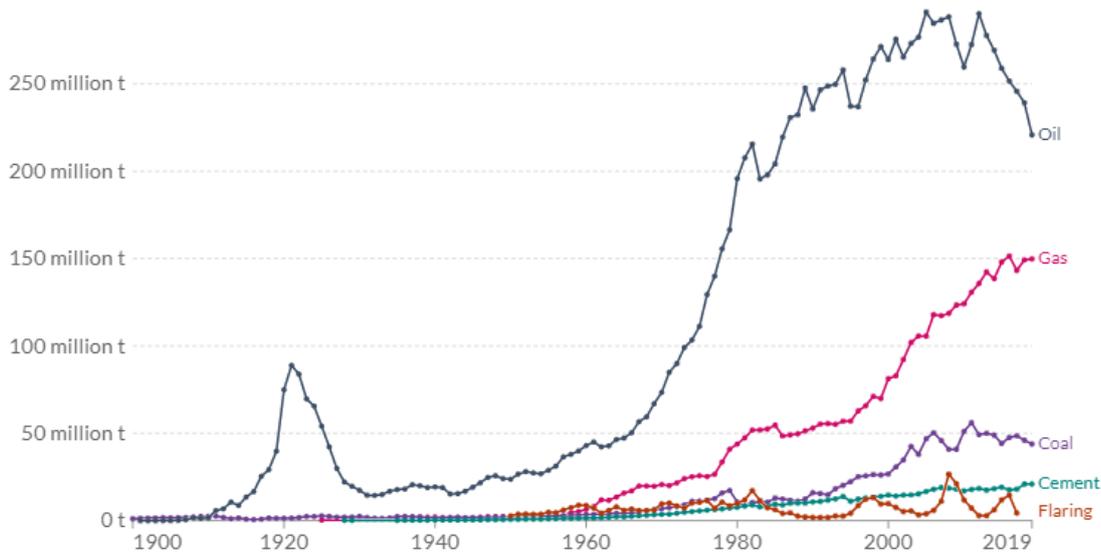
Figure 6 Green house gas emissions by sector in Mexico, from 1990 to 2019. Source: Our world in data.

In Figure 6, the Mexican sectors of emissions are presented, from 1990 to 2019. The most carbon intensive sources since at least the last three decades are the electricity, heat, transportation, and agriculture, which in many aspects are under regulation of the Mexican state. Similarly, Figure 7 shows that oil and natural gas have been the main sources of these emissions in the country. Particularly, oil sector has been historically the biggest contributor to carbon emissions, especially since 1960. This trend stagnated from the early 21st century, mainly due to the peak of oil production. Since then, natural gas has appeared as the new main fossil fuel, specifically for electricity generation.

CO2 emissions by fuel, Mexico



Change country



Source: Global Carbon Project

OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY

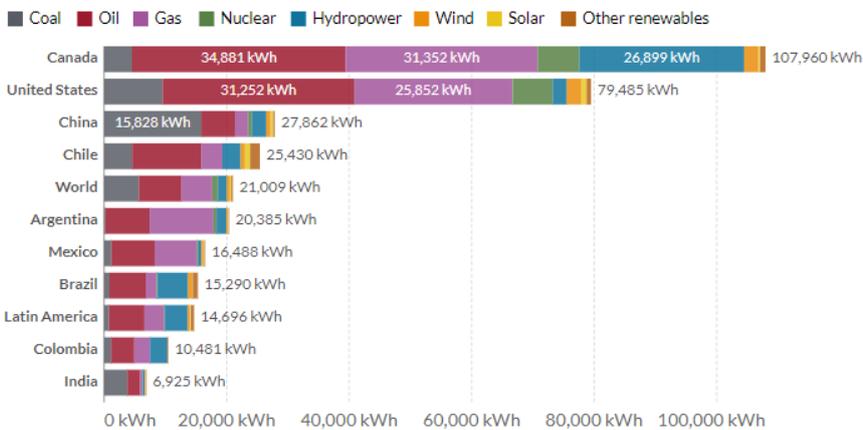
Figure 7 Carbon Emissions by Fuel in Mexico, from 1900 to 2019. Source: Our World in Data.

Per capita primary energy consumption by source, 2019



Primary energy is calculated based on the 'substitution method' which takes account of the inefficiencies in fossil fuel production by converting non-fossil energy into the energy inputs required if they had the same conversion losses as fossil fuels.

Add country Relative



Source: Our World in Data based on BP Statistical Review of World Energy

OurWorldInData.org/energy-mix • CC BY

Figure 8 Per capita primary energy consumption, 2019. Source: Our world in Data.

In a Regional context, Mexican energy systems can be viewed as an important player in the Latin American region, and even in the American as a continent region. In terms of population, Mexico accounts for 1.66% of global total and 12.66% of American continent. In terms of GDP, it accounts with the 5% of the continent. The Mexican primary energy consumption is around 5% of the total consumed in the continent, like its annual CO₂ emissions. This can be observed

Countries in America	Population (Million)	% World	% LAC	GDP (Billion USD)	GDP per capita (KUSD)	% World	% LAC	Primary Energy Consumption (TWh)	PEC per capita	% World	% LAC	Annual CO ₂ emissions (Million tons)	% World	% LAC	Emissions per capita (Million t)
Argentina	44.78	0.581%	4.44%	437.81	9.777	0.52%	1.66%	939	20.97	0.58%	2.34%	167.57	0.46%	2.23%	3.74
Bahamas	0.38	0.005%	0.04%	11.26	29.632	0.01%	0.04%	16	42.11	0.01%	0.04%	2.64	0.01%	0.04%	6.95
BELIZE	0.39	0.005%	0.04%	1.66	4.256	0.00%	0.01%	4	10.26	0.00%	0.01%	0.65	0.00%	0.01%	1.67
Bolivia	11.51	0.149%	1.14%	27	2.346	0.03%	0.10%	91	7.91	0.06%	0.23%	23.85	0.06%	0.32%	2.07
Brazil	211.05	2.737%	20.94%	2360	11.182	2.78%	8.96%	3450	16.35	2.14%	8.60%	485.79	1.32%	6.47%	2.30
Canada	37.41	0.485%	3.71%	1950	52.125	2.29%	7.40%	4014	107.30	2.48%	10.01%	582.39	1.59%	7.75%	15.57
Colombia	50.34	0.653%	5.00%	394.84	7.843	0.46%	1.50%	530	10.53	0.33%	1.32%	90.42	0.25%	1.20%	1.80
Costa Rica	5.05	0.065%	0.50%	51.33	10.164	0.06%	0.19%	66	13.07	0.04%	0.16%	8.82	0.02%	0.12%	1.75
Chile	18.95	0.246%	1.88%	285.04	15.042	0.34%	1.08%	468	24.70	0.29%	1.17%	86.13	0.23%	1.15%	4.55
Cuba	11.33	0.147%	1.12%	77.12	6.807	0.09%	0.29%	109	9.62	0.07%	0.27%	22.52	0.06%	0.30%	1.99
Dominican Republic	10.74	0.139%	1.07%	85.94	8.002	0.10%	0.33%	123	11.45	0.08%	0.31%	27.52	0.07%	0.37%	2.56
Ecuador	17.37	0.225%	1.72%	88.52	5.096	0.10%	0.34%	207	11.92	0.13%	0.52%	36.76	0.10%	0.49%	2.12
El Salvador	6.45	0.084%	0.64%	23.11	3.583	0.03%	0.09%	46	7.13	0.03%	0.11%	6.85	0.02%	0.09%	1.06
Guatemala	17.58	0.228%	1.74%	55.87	3.178	0.07%	0.21%	100	5.69	0.06%	0.25%	21.93	0.06%	0.29%	1.25
Haiti	11.26	0.146%	1.12%	14.02	1.245	0.02%	0.05%	13	1.15	0.01%	0.03%	3.29	0.01%	0.04%	0.29
Honduras	9.75	0.126%	0.97%	21.87	2.243	0.03%	0.08%		0.00	0.00%	0.00%	10.79	0.03%	0.14%	1.11
Jamaica	2.95	0.038%	0.29%	14.37	4.871	0.02%	0.05%	43	14.58	0.03%	0.11%	8.05	0.02%	0.11%	2.73
Mexico	127.58	1.655%	12.66%	1310	10.268	1.54%	4.97%	2098	16.44	1.30%	5.23%	435.51	1.19%	5.80%	3.41
Nicaragua	6.55	0.085%	0.65%	11.64	1.777	0.01%	0.04%	29	4.43	0.02%	0.07%	5.67	0.02%	0.08%	0.87
Panama	4.25	0.055%	0.42%	50.54	11.892	0.06%	0.19%	123	28.94	0.08%	0.31%	12.29	0.03%	0.16%	2.89
Paraguay	7.04	0.091%	0.70%	37.2	5.284	0.04%	0.14%	130	18.47	0.08%	0.32%	8.52	0.02%	0.11%	1.21
Peru	32.51	0.422%	3.23%	210.98	6.490	0.25%	0.80%	329	10.12	0.20%	0.82%	54.98	0.15%	0.73%	1.69
Trinidad and Tobago	1.38	0.018%	0.14%	20.81	15.080	0.02%	0.08%	197	142.75	0.12%	0.49%	40.38	0.11%	0.54%	29.26
Uruguay	3.46	0.045%	0.34%	49.56	14.324	0.06%	0.19%	68	19.65	0.04%	0.17%	6.58	0.02%	0.09%	1.90
USA	329.06	4.268%	32.66%	18350	55.765	21.60%	69.64%	26360	80.11	16.32%	65.72%	5260	14.33%	70.01%	15.98
Venezuela	28.52	0.370%	2.83%	400	14.025	0.47%	1.52%	542	19.00	0.34%	1.35%	99.18	0.27%	1.32%	3.48
SUM	1007.64	13.069%		26351.4		31%		40107				7513.63	20.47%	99.99%	
World	7710			84970				161531				36700			

Figure 9 Population, GDP, Primary Energy Consumption, Annual CO₂ emissions of American countries, 2019. Source: Our World in Data.

in figure 9.

Techno-Economic Perspective in Mexico.

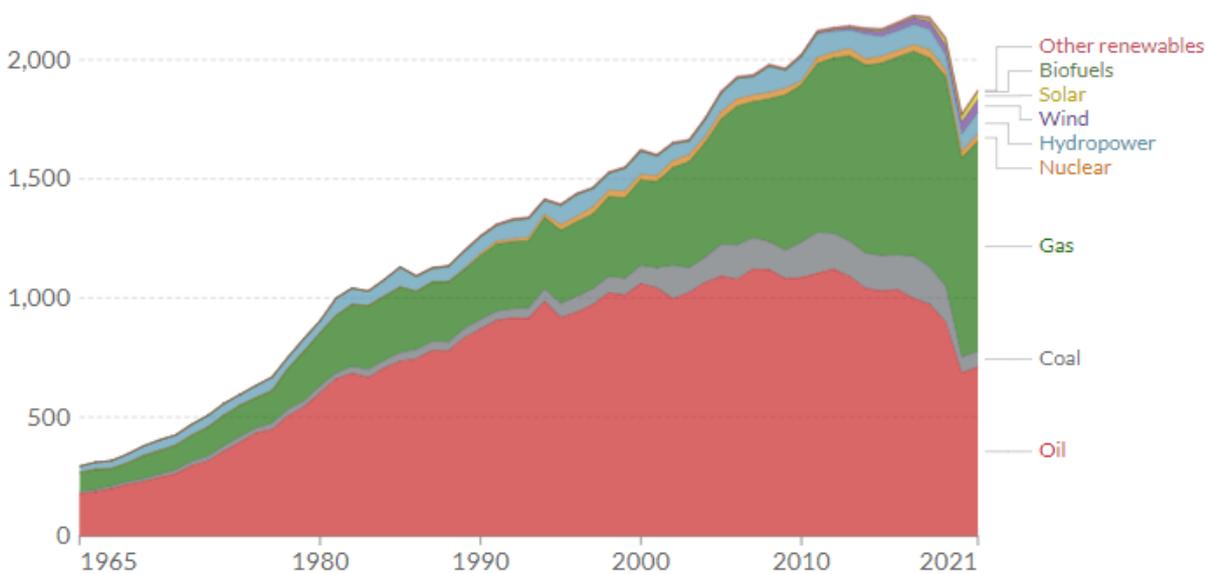
The techno-economic perspective focuses on energy flows, energy conversion processes and energy markets. Therefore, understanding the natural resources to which a country has access, as well as the energy demand it requires, is an important part of this perspective. Infrastructure is also relevant, as it is how resources are processed and distributed to the means of consumption. The purpose of this section is to present information on Mexican energy resources, supply, demand, consumption, and infrastructure of its current energy system.

Energy consumption by source, Mexico

Primary energy consumption is measured in terawatt-hours (TWh). Here an inefficiency factor (the 'substitution' method) has been applied for fossil fuels, meaning the shares by each energy source give a better approximation of final energy consumption.



↔ Change region □ Relative



Source: BP Statistical Review of World Energy

Note: 'Other renewables' includes geothermal, biomass and waste energy.

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Figure 10 shows the primary energy consumption in Mexico, from 1965 to 2021. It is noticeable oil increase from 1970's until the first decade of XXI century. Since then, natural gas started its slow but continuous rising on Mexican energy matrix, until 2020, when it overtook oil as the most used fuel in the country. The use of these fuels, however, is very different. While oil is mainly used to meet the needs of the transportation sector, through internal combustion engines, natural gas has been used as an energy source for electricity generation, mainly in

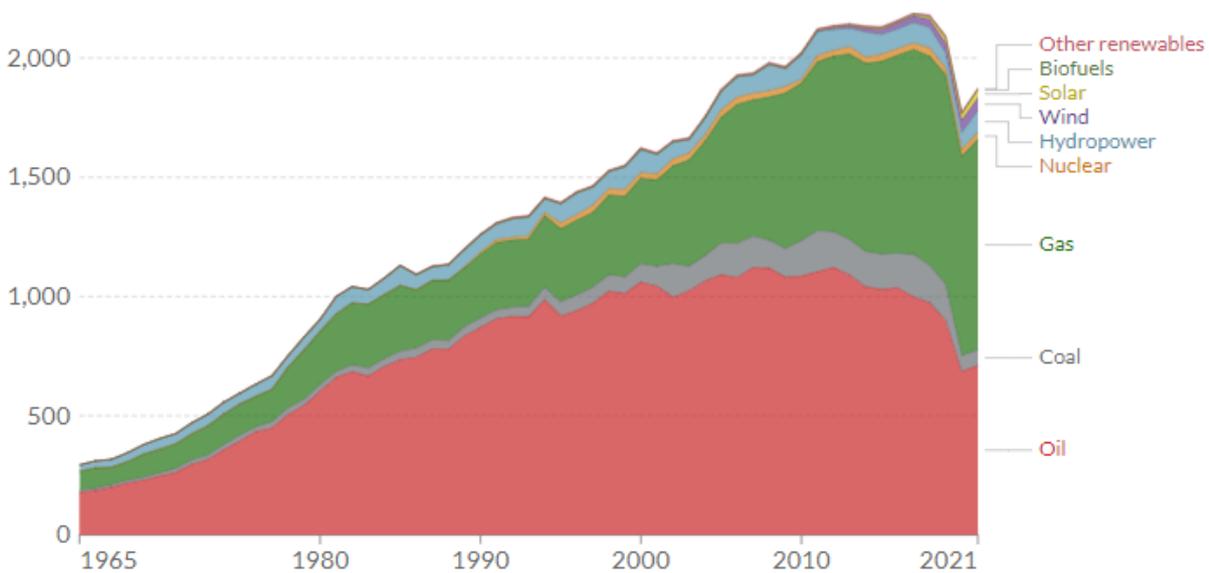
combined cycle gas-steam plants, in which gas is burned in a gas turbine and then the exhaust gases pass to a Heat Recovery Steam Generator (HRSG), where that heat will be used to generate another portion of electricity in a steam cycle.

Energy consumption by source, Mexico

Primary energy consumption is measured in terawatt-hours (TWh). Here an inefficiency factor (the 'substitution' method) has been applied for fossil fuels, meaning the shares by each energy source give a better approximation of final energy consumption.



Change region Relative



Source: BP Statistical Review of World Energy
Note: 'Other renewables' includes geothermal, biomass and waste energy.

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Figure 10 Primary Energy Consumption in Mexico, from 1965 to 2021. Source: Our World in Data.

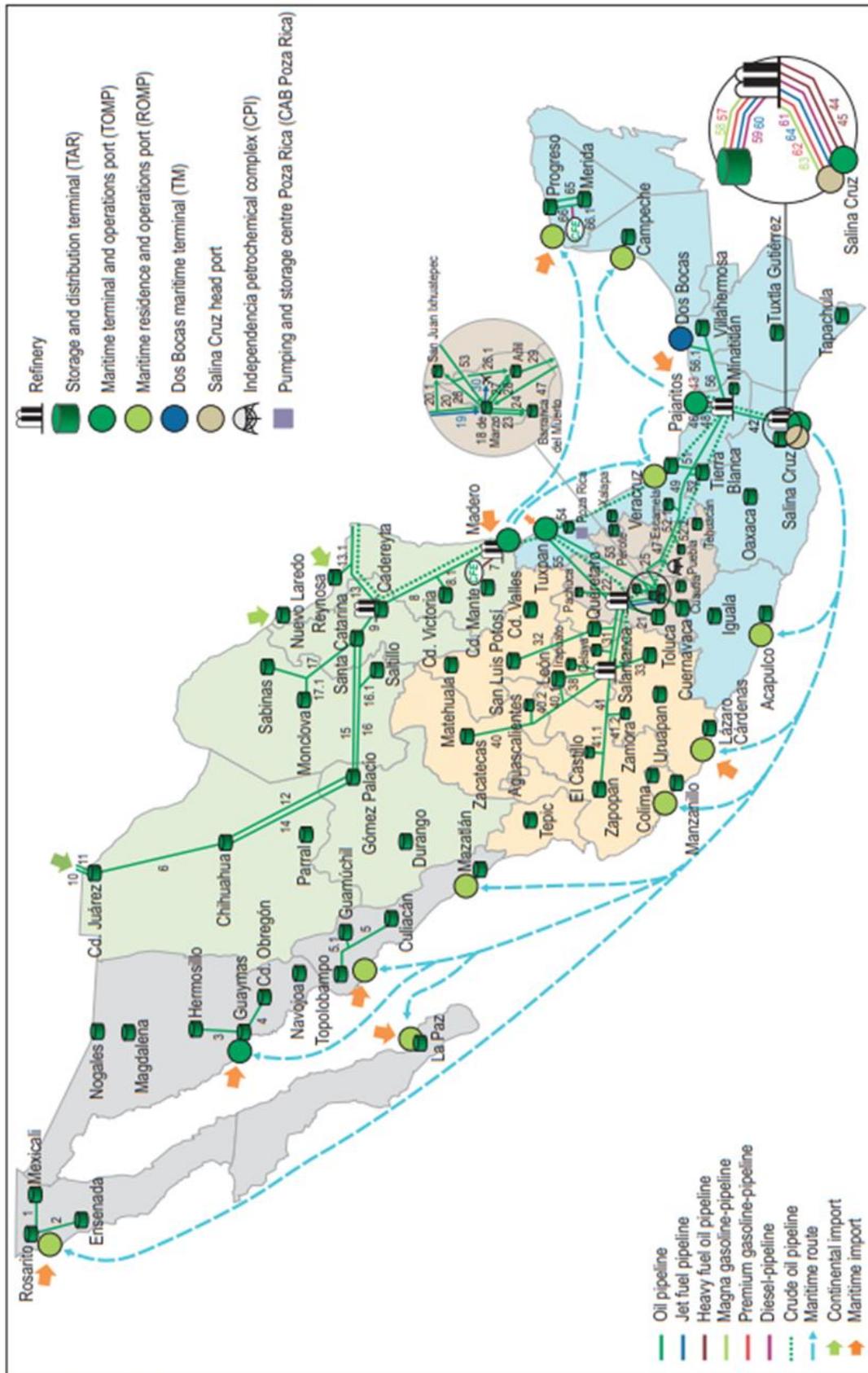
The most conventional way to produce electricity has been the thermoelectric power plants, where heat is used in a boiler to produce steam at high pressure and temperature, then this steam goes through power turbine, which moves an electric generator, producing the electricity. At the end of the steam turbine, the steam at low pressure and temperature is directed to a condenser, just before returning to the boiler to repeat the cycle. The origin of this heat may be any kind of fuel, from solar thermal, nuclear, biofuels or most likely, coal or natural gas.

Nuclear power plants are similar in the way that also produce steam to generate the electricity, but the source of that heat is not from fossil fuels, but from a nuclear reactor, in which a

controlled fission reaction releases the heat to produce the steam. After the oil crises of the 70's, nuclear energy had a higher relevance in the power generation business, the light water reactor won the internal race between nuclear technologies to produce electricity, mainly because it was available, it worked well, and it was economically affordable. Another interesting fact about this kind of technology, is that also can use energy efficiency projects like cogeneration.

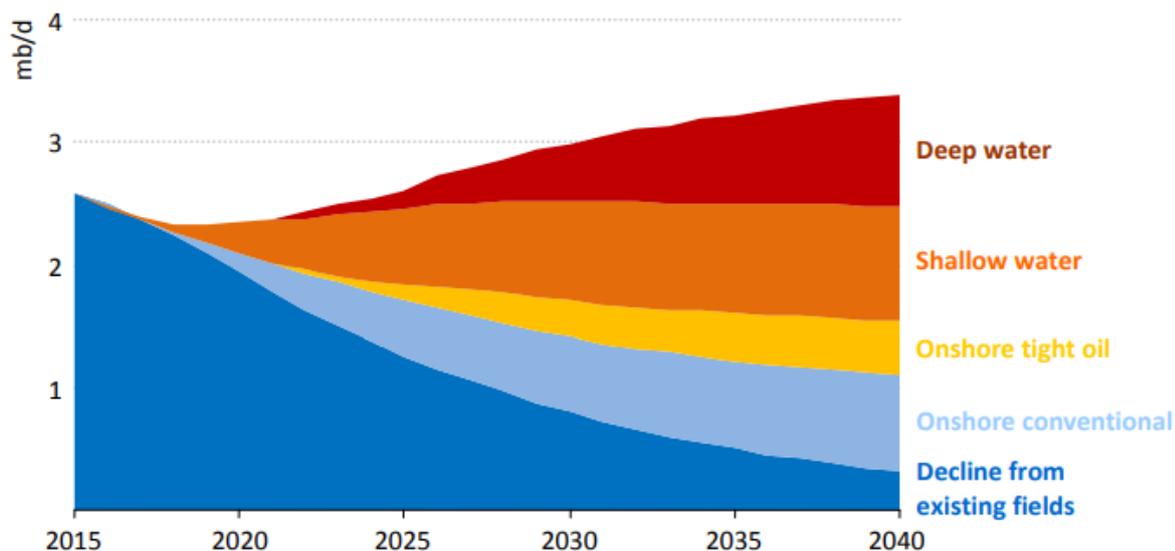
Mexico is a country known for its oil production, specially at the end of XX century and the beginning of the XXI century. This fossil fuel is an oily organic material in form of liquid at atmospheric temperature and pressure. This fuel had an exponential growth consumption in the XIX century, mainly because of the energy requirements needed to fuel the industrial revolution in Western Europe and the USA. The first oil drills registered in the USA are from around 1874. Since then, this country has been a major producer and consumer of this good. It is the main raw material to produce gasolines, jet fuel, petrochemicals, kerosene, diesel, fuel oil and liquified petroleum gas. In Figure 11 Oil Infrastructure in Mexico, 2016. Source: SENER. it is shown the best arrangement of pipelines and maritime routes of cylinders to carry the fuel.

Figure 12 presents the oil production expected in the next decades. Oil production from existing fields will continue to decline, so more production will be required from onshore, shallow water and deep-water fields, for which a much larger investment will be necessary, which are usually shared with other private oil companies. This suggests that Mexico should find other sources of energy to meet the demand expected to be covered with this fuel, which is mainly the transportation sector.



Source: SENER (2016).

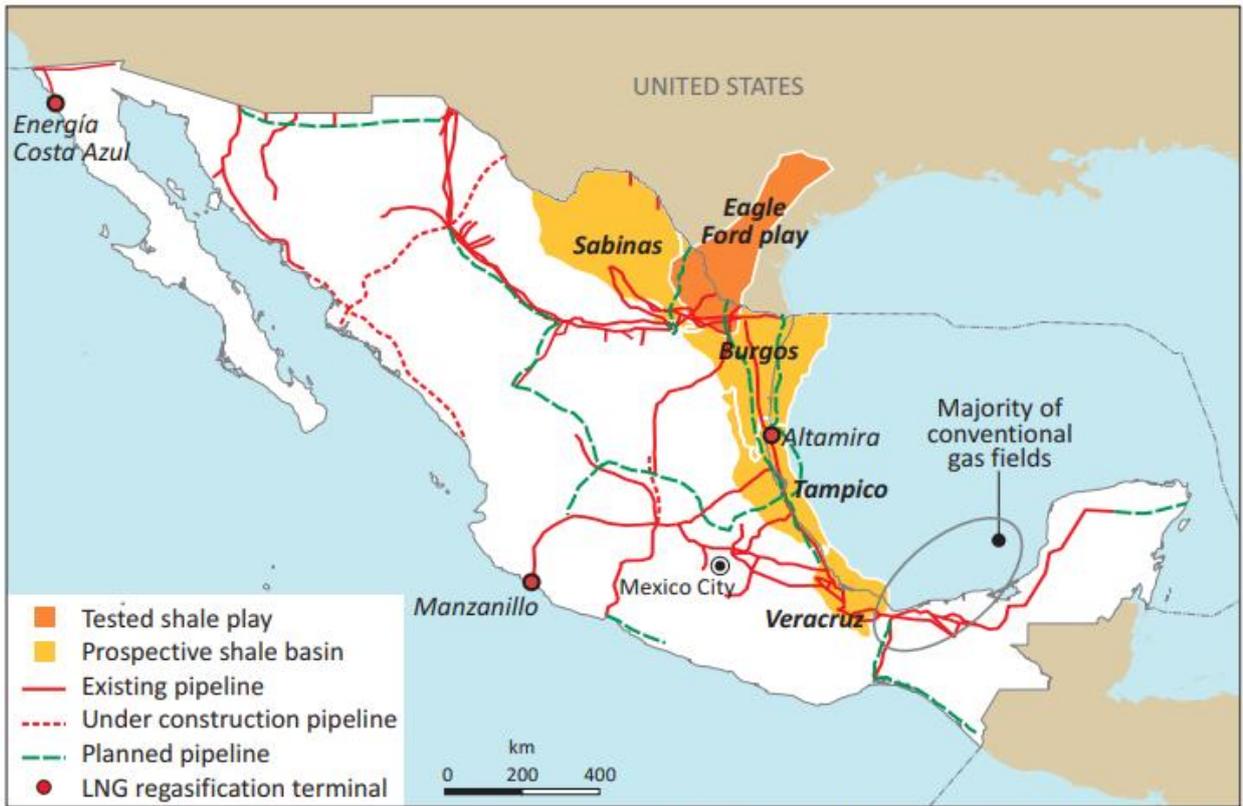
Figure 11 Oil Infrastructure in Mexico, 2016. Source: SENER.



Mexico's oil output gets back on a rising path in the New Policies Scenario, but it takes time for new projects to offset declines

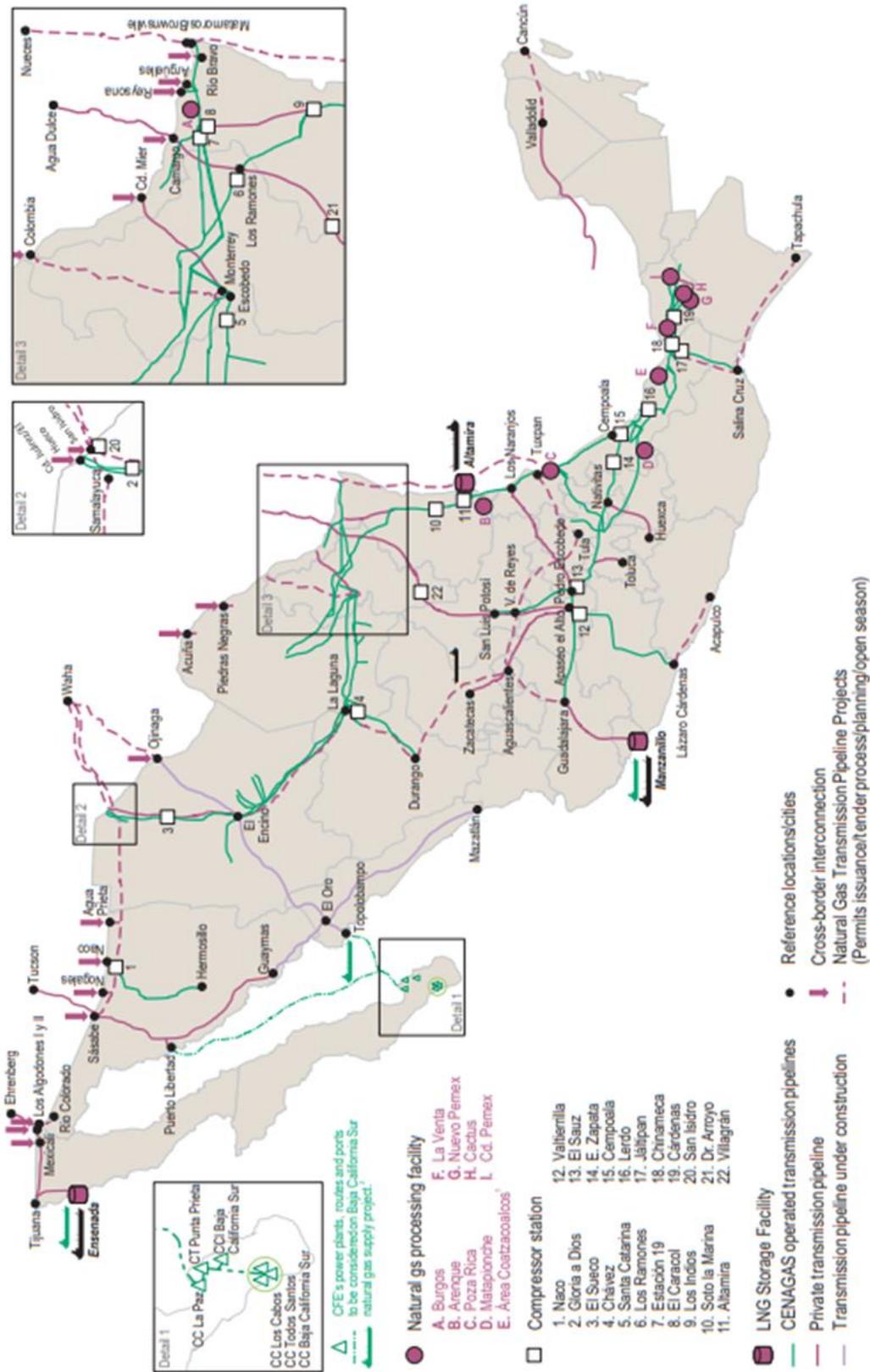
Figure 12 Oil Production in Mexico in the New Policies Scenario, 2015-2040. Source: IEA, 2016

Natural gas is a fossil fuel, mainly constituted by methane and other hydrocarbons. From Rincon 2021, it is known that Mexico possesses just 0.01 % of global natural gas deposits, and that most of the national consumption of this resource comes imported from the USA. Still, there are plans to build new pipelines increase this trend, mainly because this fuel is increasingly replacing oil in electric power generation. Figure 13 and 14 show the current and planned infrastructure of Natural Gas in Mexico, such as public and private pipelines, processing facilities, LNG storage facilities and compression stations. It can be observed that the Mexican gulf possess a prospective shale basin for acquiring this resource. Likewise, Figure 15 shows the projection estimated by the IEA for natural gas production from 2005 to 2040. It can be seen how this trend of dependence on natural gas imports is expected to increase to 50% of demand, among the years 2020 and 2030.



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

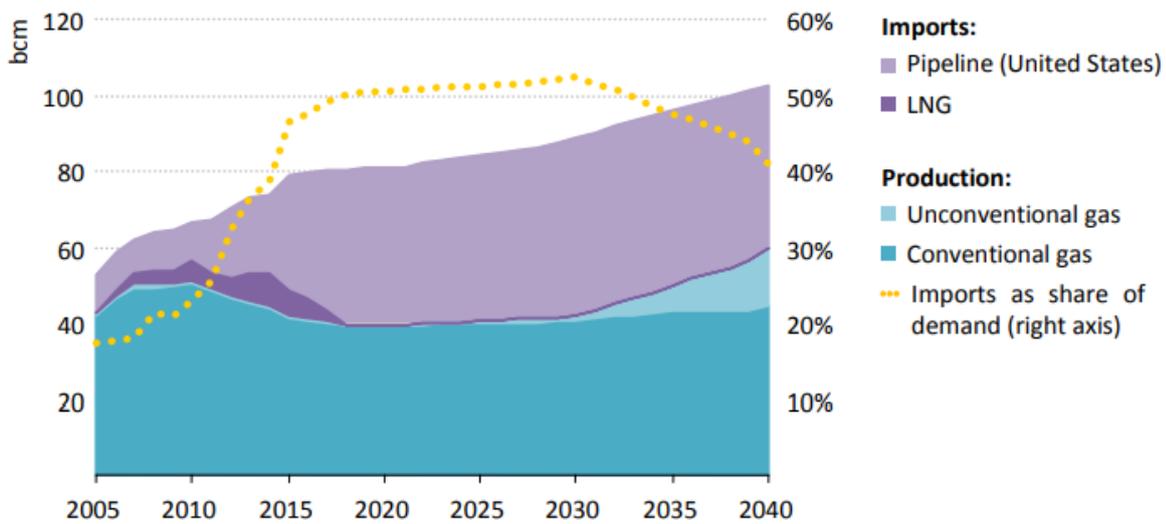
Figure 13 Infrastructure and Resources of Natural Gas in Mexico. Source: IEA, 2016



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Source: SENER (2016b).

Figure 14 Natural Gas Pipeline infrastructure in Mexico. Source: IEA, 2017



Pipeline imports from the United States rise to more than half of Mexico's total gas supply

Figure 15 Natural Gas Production and imports by type, 2005-2040. Source: IEA,2016

The Mexican infrastructure is strong in terms of fuel distribution. Pipelines, roads, railroads, and maritime routes are commonly used for covering the resource necessity. This is true for both petroleum and natural gas, but not for coal. Fortunately, there is relatively no big coal production nor consumption in Mexico. Another important matter in this context is the clear dependence of a fossil fuel to cover important energy needs. Natural gas to generate electricity and Petroleum for transportation and petrochemicals. In both cases, the volatility of fossil fuel prices has affected the economy of the consumers.

In terms of the electricity sector, Figure 16 identifies the regional divisions and the 89 interregional connections of the states of the Mexican Republic, according to the national electrical system. Similarly, Figure 17 presents the electricity production by energy source in Mexico, from 1985 to 2021. It clearly shows the large increase that natural gas has had since the beginning of this century, from 35 TWh in 2000 to 170 TWh in 2020, while the other sources remain practically constant.

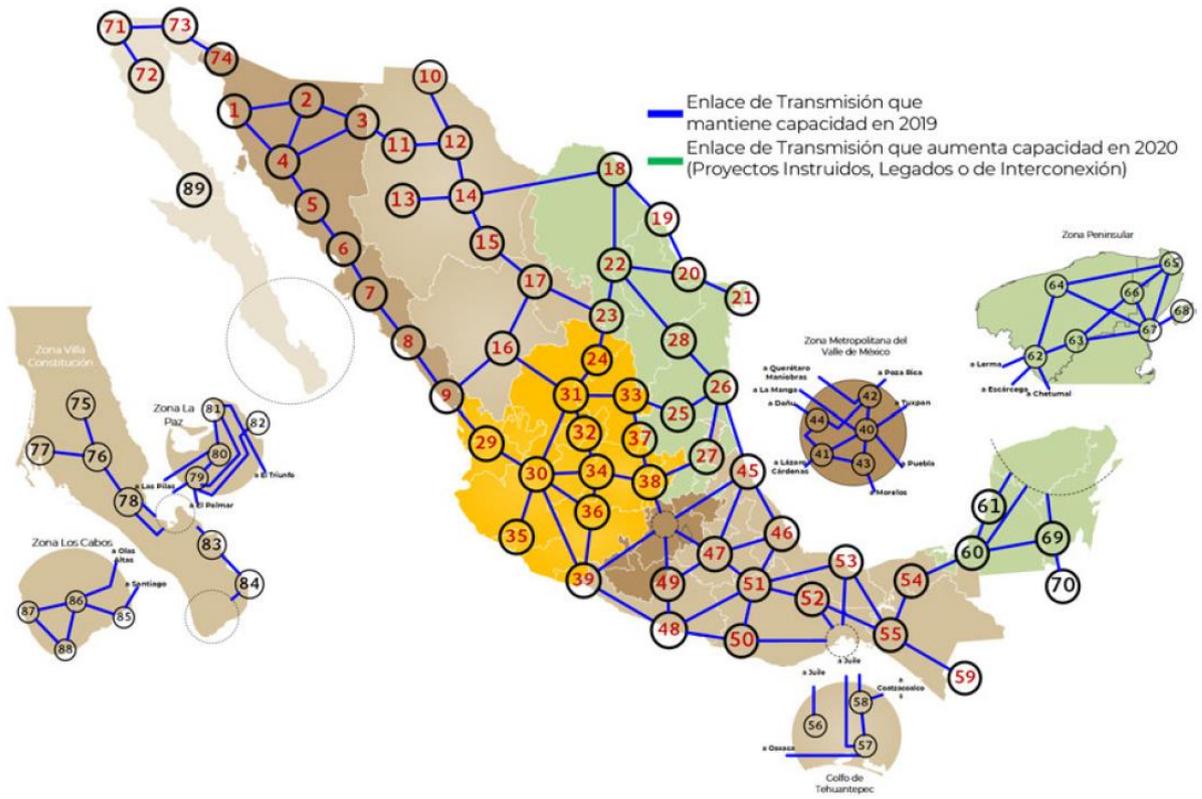
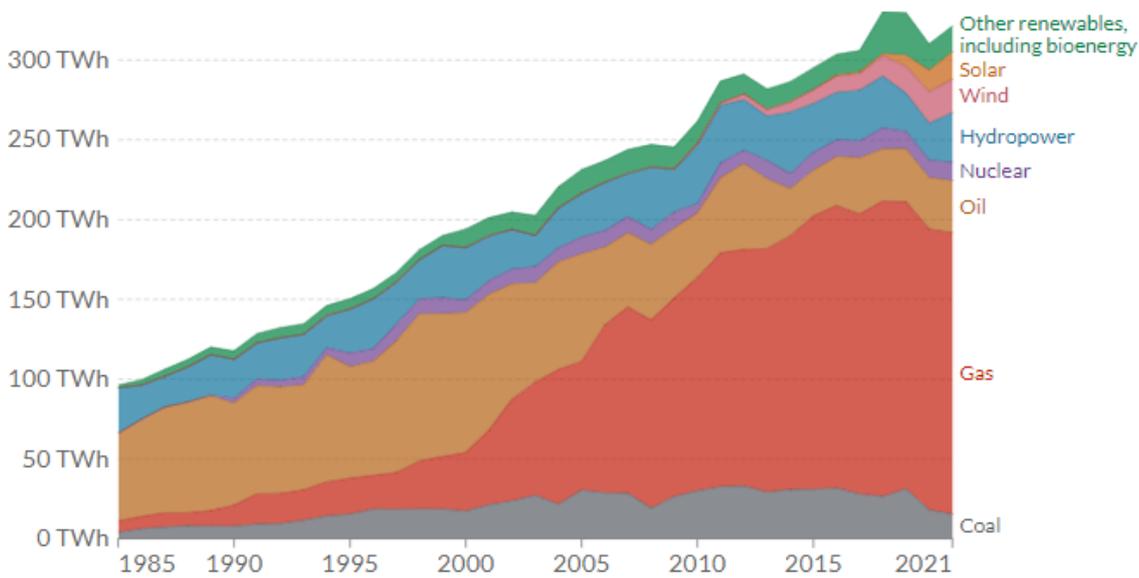


Figure 16 Regions and Interregional Connections in Transmission Lines. Source: SENER and CENACE, 2020

Electricity production by source, Mexico

Change country Relative



Source: Our World in Data based on BP Statistical Review of World Energy, Ember Global Electricity Review (2022) & Ember European Electricity Review (2022)
 Note: 'Other renewables' includes biomass and waste, geothermal, wave and tidal.
 OurWorldInData.org/energy • CC BY

Figure 17 Electricity production by source in Mexico, from 1985 to 2021. Source: Our World in Data.

From Rincon (2021), it is known that the world receives from the sun to its surface at least 5,000 more energy than what is consumed. Just Eolic energy, it accounts to 200 times. By far, solar energy is the most abundant energy source. The inconvenient is that current infrastructure to take advantage of this resource is not developed, yet. Figure 18 shows the Mexican installed solar capacity, which has been increasing continuously since 2015.

Installed solar energy capacity

Cumulative installed solar capacity, measured in gigawatts (GW).

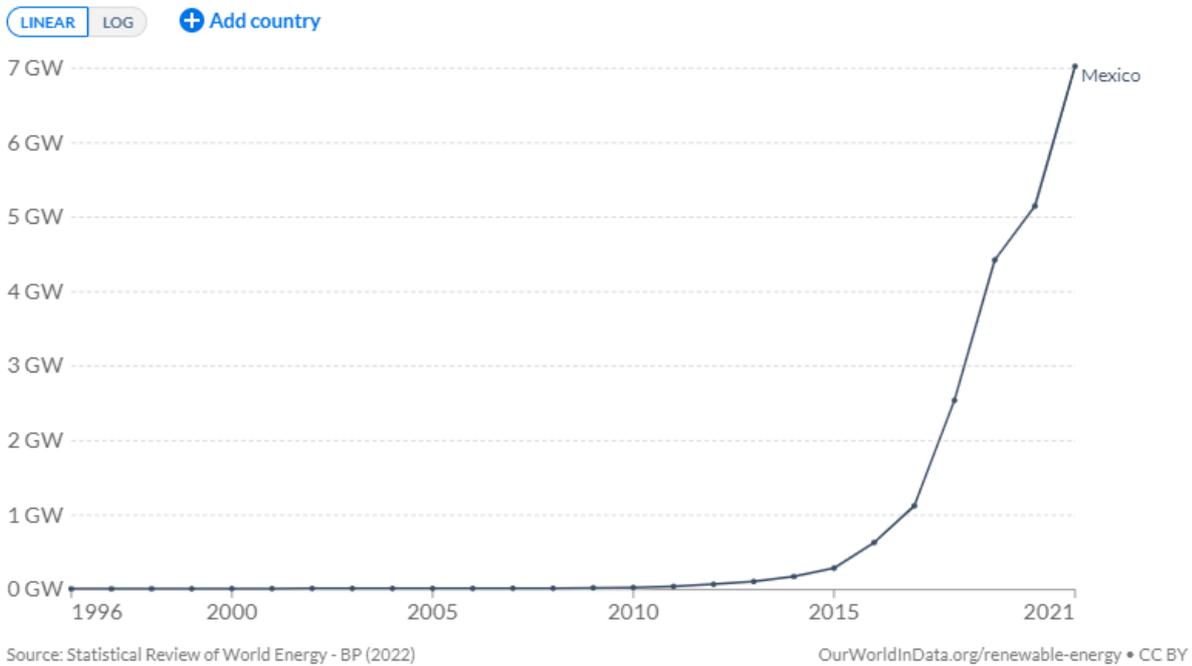


Figure 18 Installed Solar Energy Capacity. Source: Our World in Data.

According to the report “Country Analysis: Mexico” by the USA Energy Information Administration, in 2019, Mexico was one of the largest providers of USA oil imports, with around 600,000 barrels per day, which means 9% USA crude oil imports. Mexico’s economy is largely fuelled by petroleum and other petrochemicals.

The Mexican Clean Energy report, made by the National Renewable Energy Laboratory (NREL), and the Department of Energy (DoE) of USA, estimated an energy demand of 365 TWh by 2024. In the same document, they acknowledge the national solar PV capacity potential of 24,918 GW, which would be able to generate 50,196 TWh per year. Additionally, the Mexican wind capacity is estimated at 3,669 GW, able to generate 5,759 TWh/yr. Also, the report points that rapid growth in renewable energy could generate high levels of investment and reduce costs to consumers, while improving reliability and resilience of Mexico’s power systems. Therefore, the biggest challenges to solve are the integration of inverters and synchronous machines to deal with the variability and uncertainty of renewable energy sources.

The results of this perspectives are clear. Based on the quantitative analysis of resource capacity, infrastructure, and energy market flows, it may look obvious for a successful sustainable transition to switch from a carbon intensive, non-renewable and scarce fuel to the available, abundant, cheap, and clean energy sources. In the past, it was argued that renewable energies were not a smart option because of the economic feasibility. It was too expensive, and renewables were not reliable. The reliability of the energy system was going to be compromised, experts used to say. Nowadays, that statement is not accurate anymore. For the first time ever, it is cheaper to produce electricity from a clean and renewable source than with a pollutant fossil source. But the risk is not in the carbon intensity of the energy generation, but in the overall energy consumption, mainly due to the mines needed to cover the materials requirement to produce solar panels, wind turbines, electrolysers, etc.

Peña Sanchez et al (2021) affirm that in Mexico, 54 PWh of renewable energy can be produced at a Levelized cost of electricity of less than Euro 70/MWh, most of it would come from open photovoltaic solar energy, using 27 TW of installed capacity in 578,000 km², roughly ¼ of total land surface of the country. Similarly, Rincón (2020) mentions that a solar photovoltaic capacity of 8 TW would be enough to satisfy current and future energy requirements. The smart location of new renewable energy power plants will be imperative. As Cherp (2021) has affirmed, if solar photovoltaic and wind continue to grow at roughly their current rates for just one more decade, they will provide almost as much electricity as the entire power generation system produces today.

Highlights:

- Since 2005, more than 95% of Mexican population has access to electric energy. This is defined as having an electricity source that can provide very basic lighting and charge a phone or power a radio for 4 hours per day.

- Mexico consumes around 2,000 TWh of fossil fuel energy per year. Oil and Natural gas are the biggest fuels consumed, around 850 TWh each one per year, and coal around 150 TWh.
- Annual Coal production is around 75 TWh, Consumption is 150 TWh.
- Annual Oil production is 1,200 TWh and it is expected to keep decreasing. Consumption is 950 TWh.
- Annual Natural gas production is 400 TWh, consumption in 2019 was 880 TWh and it is expected to keep rising.
- Annual solar potential capacity is **24,918 GW**, able to generate **50,196 TWh**.
- Annual wind potential capacity is **3,669 GW**, able to generate **5,759 TWh**.
- Infrastructure in electric grid, mainly in transmission, distribution, and electric storage is required.

Socio-Technical Perspective in Mexico.

This section presents the results of the socio-technical perspective in the Mexican energy sector. Based on the results of the technical-economic perspective and understanding that innovation systems must be aimed at solving the carbon intensity problems of current energy systems, this section presents some technologies and their relationship in the environment of the Mexican energy system.

Based on the key points of the techno-economic perspective, it can be assumed that lock-in issues are a current problem in Mexican energy sector. Infrastructure on oil and natural gas, especially pipelines, represent a considerable investment that both national government and private sector will need to pay back. Some of the technologies that can represent an innovative change and are considered in these sections are energy efficiency for generation and consumption, hydrogen produced by renewable energies and carbon capture and storage.

One of the most important technologies to understand is energy efficiency. As IEA usually refers, energy efficiency is the most important way to reduce cost of operation, by retrofitting buildings and infrastructure of an energy process. Reaching net zero emissions by 2050 seems out of reach in the absence of a mayor acceleration of clean energy technology innovations, particularly in sectors such as power generation, transport, and industry. Today, where energy prices are so relevant, energy efficiency is one of the best ways to decarbonize energy consumption and obtain an increased output of useful energy from the combustion of the everyday more expensive fossil fuels. It represents a real incentive to accept projects.

For example, adding sensors to the energy systems and monitor energy, from the production to the consumption. Homes does not consume a high amount of energy compared to industry, transport, and feedstock. Smart meters help to measure, and therefore, control energy flows.

Smart meters only give the total amount of energy. They don't tell where the leaks are, where are the best cost competitive solutions.

Since 2015, the IEA has an annual conference on Energy efficiency, in which they expose the energy efficiency policies of some of their member states, their success cases. In the 2022 conference, hosted in Denmark, it was emphasised the importance of this tool to decarbonize global energy systems. Unfortunately, this kind of implementation generates savings from the fuel consumption avoided, but not necessarily generates revenues by itself.

Regarding hydrogen produced from renewable energy sources, or green hydrogen, Szabo (2020) argues about the gas bridge concept, a tentative solution to stop dependence on natural gas would be to replace it with hydrogen, but if this energy carrier is not from renewable sources, the dependence for fossil fuels will remain intact. This is particularly the case for the Mexican energy sector. Green hydrogen represents the opportunity to store surplus electrical energy produced by renewable energy sources, which provides the opportunity to use this fuel by conventional means, or even to export it if the energy demand has been covered.

In the study Cost-competitiveness of green hydrogen by Oxford Institute for Energy Studies (2021), Patonia and Poudinesh mentioned that currently the production of hydrogen from technology of electrolyzers is between 2 and 6 times more expensive than the one from fossil fuels, so innovation in both electrolyzers' efficiency and production materials. Green hydrogen can be defined as the first element on the periodic table, produced by the process of electrolyzers, using as the source of energy the electricity provided by renewable energies, such as solar or wind. In that scene, hydrogen is seen as an important step on the road to full decarbonization. In Mexican context, the German Mexican cooperation (giz) released the roadmap for Mexico to develop the necessary infrastructure to produce green hydrogen.

Highlights:

Considering the high dependence on oil and natural gas to satisfy the transportation and power generation sector, and to avoid lock-in constraints, the most convenient innovation systems for the energy system in Mexico are:

- Integration of renewable energy systems to the current grid.
- Energy efficiency in power generation systems and in consumption sector.
- Hydrogen produced from renewable energy.

Political Perspective in Mexico.

This section indicates the most relevant aspects of the political perspective in the Mexican energy system. As previously discussed, this perspective focuses on the state goals, the international context, political interests, capacities, and institutions. In the Mexican context, it is relevant to understand past decisions on energy policy. In 2013, the federal government in turn approved the energy reform, in which the market for electricity generation and hydrocarbon exploration in national territory was opened for the private sector, which was exclusive to parastatal companies CFE (state utility company) and PEMEX (state oil and gas company), before the approval of this reform.

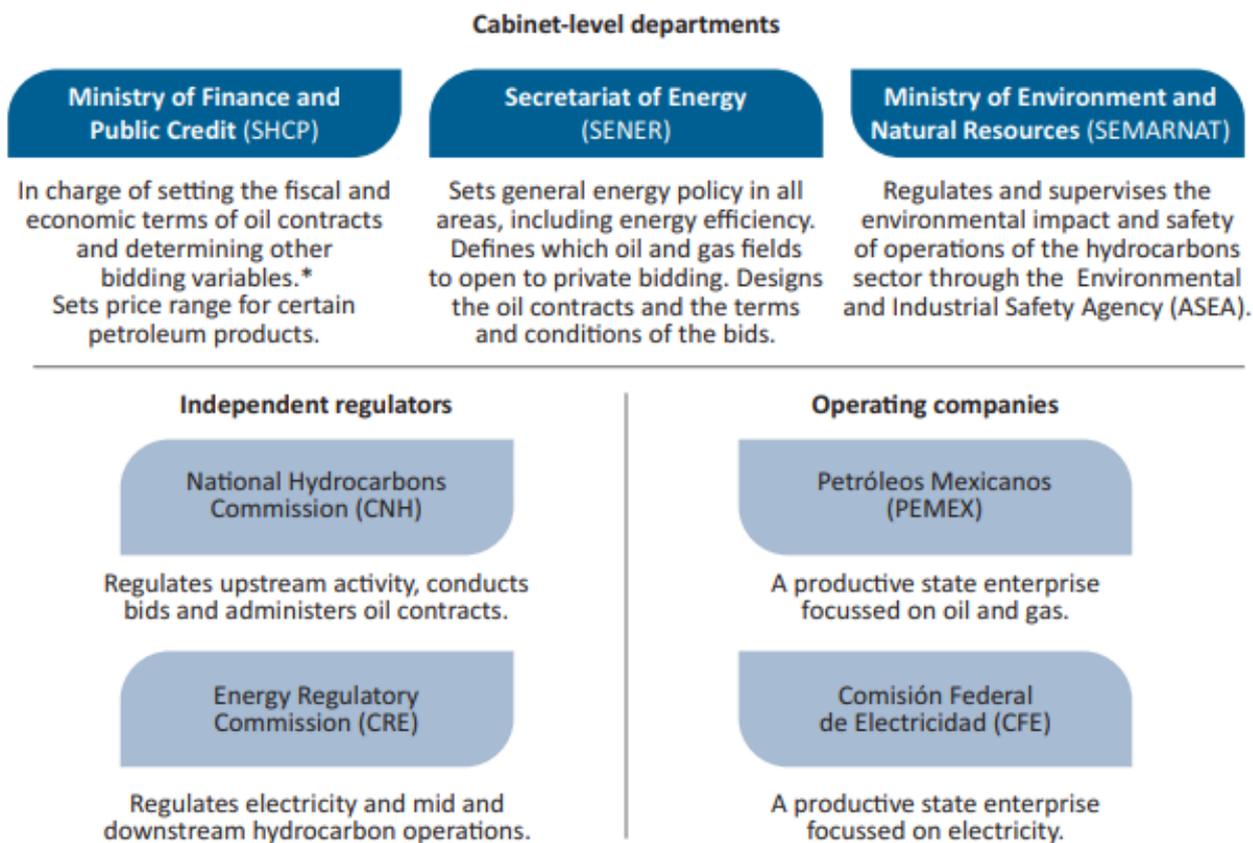
Since 2018, with the arrival of a different political party to the federal government, a counter-reform was presented, which argued that the PEMEX and CFE companies, which were now productive State companies, had been severely weakened due to this energy reform, as it disproportionately favoured transnational energy companies. The discussion regarding energy policy is mainly a discussion of nationalization or liberalization of the hydrocarbons and electricity market. The generalized discourse is about being in favour or against of a National Utility company that invest in fossil fuels and compromises the renewable energy investments, or the solar and wind private companies that currently have cheaper energy prices but lack the legal rights to sell their electricity. In the meantime, every year, the country releases more than 450 Mt of carbon emissions, and around 1 million Mexican citizens still don't have access to electricity.

The National Electric System Development Program (PRODESEN) 2021-2035, establishes the road map regarding the electric power generation systems in the country for the next decade. The document established that the combined cycle plants are the ones that will continue to dominate the market, with more than 50% of the electricity generation to cover the increasing

demand. It is argued that the current infrastructure does not have sufficient capacity to increase the capacity of electricity generation by renewable sources, so imports of natural gas will continue.

An important tool in Mexico is the Emissions trade system, which has been supported by giz, the German cooperation institution. This system started a prototype phase in 2019 and is expected to start operations by 2023. Another tool is the official register of carbon emissions of companies with more than 100,000 tons of CO₂ per year. Since 2016, for example, most of the industries, including CFE and PEMEX, declare their annual emissions at the National Emissions Register.

Figure 19 presents the arrangement of cabinet-level departments, independent regulators and operating companies introduced by the energy reform proposed in 2013. The Ministry of Finance and Public Credit, Secretariat of Energy and the Ministry of Environment and Natural Resources were the 3 main pillars of the cabinet departments, followed by PEMEX and CFE as the operating companies for oil and gas, and electricity, respectively. The activities of the operating companies would be audited by the independent regulators.



The Reform introduced fundamental changes to energy governance in Mexico

*These include parameters such as proposals for a programme of work, which is a factor in determining the winning bidder.

Figure 19 Public Institutions Influencing Energy Policy in Mexico. Source: IEA, 2016.

Similarly, figure 20 shows the arrangement of power generation, system control and market, retail and consumption proposed in the reform of 2013. In the generation section, the new feature would be the private parties, which in 2020 accounted for more than 50% of share of the national electricity generation, being one of the reasons for the counter reform proposed by the current government.

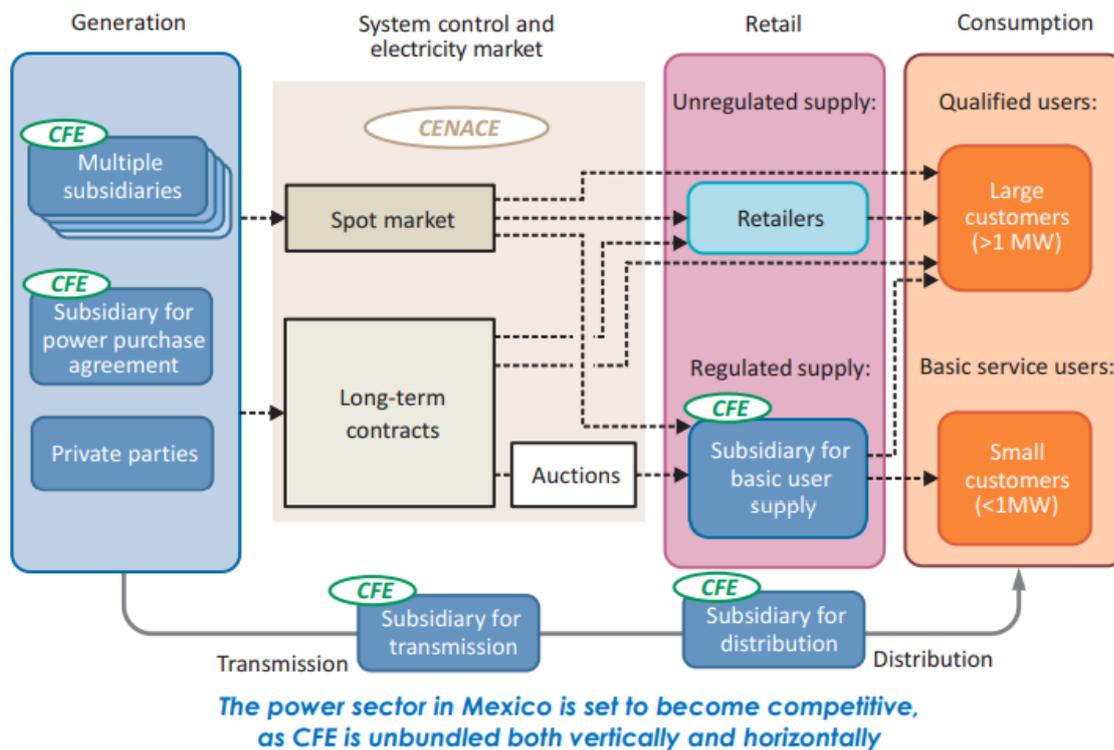


Figure 20 Structure of Mexican power sector under Energy Reform 2013. Source: IEA, 2016.

Currently, there are at least 3 big climate policies in Mexico, which are the General Law on Climate Change, the National Strategy on Climate Change and the intended NDC presented to the UNFCCC. (Solano-Rodríguez et al. 2018). Unfortunately, none of them are taking an important role in the national energy sector.

Highlights:

- Cabinet-level departments, such as the Secretariat of Energy and the Ministry of Environment and Natural Resources must include decarbonization pathways in their activities.
- PEMEX and CFE must transform their operations, physically and institutionally.
- Laws and Treaties may be considered in a plan of decarbonization.
- Public policy is a main driver to decarbonize energy systems.

- There are several reliable reports and documents on advice for policy makers to decarbonize energy systems.

5. Discussion

In this section, an interpretation of the highlights of each of the perspectives presented in the previous chapter is analysed, as well as the interrelation of these points. As mentioned before, this thesis aims to examine the set of projects that must be developed in Mexico to reach carbon neutrality in its energy sector by 2050. From the techno economic perspective, data suggests that Mexico is a country with a robust fossil fuel infrastructure, increasing problems of oil and natural gas supply, which inconveniently are its current main energy sources. At the same time, it has a renewable energy potential that far exceeds its energy demand, with the major drawback of not having adequate infrastructure to take advantage of this renewable potential.

In the Techno economic perspective, what this work intends to propose is to imagine that these systems are incomplete. Both technically and economically. If it is technologically possible to continue to produce electricity while avoiding GHG emissions into the atmosphere, then, more than at any other time, this must be done. The short-term economic implications are evident, the investment would represent a higher cost to implement the necessary systems, in addition to the reduction in net generation, but it would be worth it.

Regarding the socio-technical perspective, the most important points to be established on innovation systems are those that allow reducing the dependence on these fuels, through the substitution of the energy supply by cleaner means. This would allow demand to continue to grow, regardless of the natural reductions in the production of fossil fuels that the country has shown in previous years.

In terms of electricity generation, solar photovoltaic and wind power technology should be chosen, renewable energies that today are sufficiently economical to be implemented, especially in privileged resource locations, such as Mexico. Additionally, and in a complementary manner, energy efficiency systems are contaminated, both in energy generation

and consumption, as well as renewable energy storage, such as green hydrogen, whose cost currently depends largely on the technology of electrolyzers, so its development is very important, not only to use this fuel when the solar and wind resource is not available, but to potentially be exported when the national energy demand has been covered.

As for the political perspective, there is a discrepancy between discourse and reality, since despite being one of the first countries to present its environmental commitments under the Paris agreement, the current government has been dedicated to discouraging investments in renewable energy projects, in addition to using a large part of the federal energy budget for the construction of a new refinery. While the construction of this refinery may provide energy and environmental security for the country, it will not be the only way to achieve this goal.

An important point to consider is the public policy for the use of current infrastructure as the basis for future infrastructure for low-carbon energy systems. If the technical-economic requirements are met and it is applied in a system of diffusion of technological innovations, the appropriate policies could speed up the adaptation of the enormous oil and natural gas infrastructure existing in the country, from the generation to consumption areas. The main responsible for these actions are PEMEX, CFE, SENER and SEMARNAT

6. Conclusion

As discussed in previous sections, the purpose of this paper is to propose projects that promote carbon neutrality in Mexico's energy systems. This is an extremely complex task, since historically the economic development of any country has been largely linked to its level of emissions. However, this is no longer the case today, and Mexico is presented as one of the countries where its energy and geographical situation position it as privileged to carry out a sustainable energy transition.

These projects will require a transition in investments, from exploration and exploitation of fossil resources that are increasingly expensive and difficult to find, towards ones with abundance but without current infrastructure. Renewable energy generation systems are already a reality; however, this does not mean that the solution is already guaranteed. The proper implementation of energy systems will lie in a correct harmony between the supply of energy resources and their demand. That is why technological instruments such as energy efficiency and green hydrogen storage are so important for the sustainable energy transition in this country.

Despite the many challenges and drawbacks, it faces, Mexico has an enormous potential to achieve carbon neutrality even before the year 2050, creating a modern, reliable, efficient, resilient, and low-carbon energy market. If it is possible to achieve the proper coupling in the reduction of its production of fossil fuels and the increase in electricity generation with solar and wind sources, in addition to energy efficiency and energy storage projects.

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